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GEOLOGICAL SURVEY OF CANADA
BULLETIN 461

# GEOLOGY OF WRANGEL ISLAND, BETWEEN CHUKCHI AND EAST SIBERIAN SEAS, NORTHEASTERN RUSSIA

M.K. Kos'ko, M.P. Cecile, J.C. Harrison, V.G. Ganelin, N.V. Khandoshko and B.G. Lopatin

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**Cover Illustration**
View looking east along the central mountains of Wrangel Island. Dark rocks in the background are Triassic. South dipping strata in the foreground are Devonian to Carboniferous clastics and carbonates. (I.S.P.G. Photo 2669–1)

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# PREFACE

In 1984, Canada and the USSR entered into an Arctic Science Exchange agreement, an important theme of which is the comparison of the geological evolution of the Arctic regions of both countries. Before 1984, progress in understanding the geology of the Arctic was hindered by political and cultural barriers. Soviet and western scientists had not enjoyed easy access to each others' field areas, and this inhibited understanding and exchange of data. The 1984 agreement between Canada and the USSR[1] for scientific and technological exchange in the Arctic represents a major step forward in the pursuit of understanding the geology of the Arctic region. This report, on the geology of a remote and important Russian island, is a direct result of this exchange, and this co-operative effort will be a landmark in providing new constraints to regional plate tectonic models and in providing basic information to aid in exploration and evaluation of the resource potential of the Canada Basin region.

Elkanah A. Babcock
Assistant Deputy Minister
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# PRÉFACE

En 1984, le Canada et l'URSS ont conclu un accord d'échange de connaissances scientifiques sur l'Arctique, dont l'un des thèmes importants est la comparaison de l'évolution géologique des régions arctiques dans les deux pays. Avant 1984, des obstacles de nature politique et culturelle ont entravé les progrès accomplis pour comprendre la géologie de l'Arctique. Le fait que les scientifiques de l'Union soviétique et des pays de l'Ouest n'avaient pas facilement accès aux zones d'étude de leurs homologues a eu pour effet de ralentir la compréhension et l'échange des données. L'accord conclu en 1984 entre le Canada et l'URSS[1] en vue de l'échange des connaissances scientifiques et technologiques sur l'Arctique représente une étape importante vers une compréhension accrue de la géologie de l'Arctique. Le présent rapport sur la géologie d'une île importante et éloignée de la Russie découle directement de cet échange, et ce travail de collaboration permettra d'acquérir de nouvelles données qui aideront à préciser les modèles de la tectonique des plaques régionale ainsi que des informations de base qui faciliteront l'exploration et l'évaluation des ressources potentielles de la région du bassin Canada.

Elkanah A. Babcock
Sous-ministre adjoint
Commission géologique du Canada

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[1]This agreement continues today between the governments of Canada and Russia.
[1]Cet accord se poursuit aujourd'hui entre les gouvernements du Canada et de la Russie.

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## *Abstract*

*The oldest unit on Wrangel Island is the Upper Proterozoic Wrangel Complex, a 2000+ m succession of volcanic and clastic sedimentary rocks with small mafic and granitic intrusives and U-Pb crystallization ages of 0.63 to 0.70 Ga. The oldest Paleozoic unit is a 700 m succession of Upper Silurian and Lower Devonian clastic and carbonate strata. These strata are overlain in ascending order by: 1200 m of Devonian clastic rocks; 350 m of Lower Carboniferous clastic rocks, with conglomerate, carbonate and gypsum; 1400 m of Carboniferous carbonate with slate and bioherms; a 750 m thick unit of Permian slate and limestone, locally with olistostrome and breccia; 800 to 1500 m of Triassic flysch; and lastly, tens of metres of undeformed Tertiary and Quaternary clastics. All rock units of Proterozoic to Triassic age were pentratively deformed into north-verging structures, and metamorphosed to greenschist facies, during the Mesozoic Chukotkan Orogeny (Middle Jurassic to Early Cretaceous).*

*Some aspects of Wrangel Island's tectonic history in the circum-Canada Basin are peculiar. The most important are: Late Proterozoic magmatism; inferred latest Proterozoic–early Paleozoic orogenesis; Triassic flysch; Chukotkan deformation; and late Early Cretaceous overlap of all northeastern Russian terranes by the Upper Cretaceous Okhotsk–Chukotsk volcanic belt.*

## *Résumé*

*L'unité la plus ancienne dans l'île Wrangel est le Complexe de Wrangel du Protérozoïque supérieur, une succession de plus 2 000 m de roches volcaniques et sédimentaires clastiques que recoupent de petites intrusions mafiques et granitiques qui donnent des âges de cristallisation U-Pb de 0,63 à 0,70 ga. L'unité paléozoïque la plus ancienne est une succession de 700 m de strates clastiques et carbonatées du Silurien supérieur et du Dévonien inférieur. Ces strates reposent sous les roches suivantes, données en ordre ascendant : 1 200 m de roches clastiques dévoniennes; 350 m de roches clastiques du Carbonifère inférieur, avec du conglomérat, du carbonate et du gypse; 1 400 m de carbonates carbonifères avec de l'ardoise et des biohermes; une unité de 750 m d'épaisseur d'ardoise et de calcaire permiens, avec localement des olistostromes et des brèches; de 800 à 1 500 m de flysch triasique; et, enfin, des dizaines de mètres de roches clastiques tertiaires et quaternaires non déformées. Toutes les unités lithologiques qui s'échelonnent du Protérozoïque au Trias ont été déformées en profondeur en structures à vergence nord et métamorphisées jusqu'au faciès des schistes verts durant l'orogenèse de Chukotkan, au Mésozoïque (du Jurassique moyen au Crétacé précoce).*

*Certains aspects de l'histoire tectonique de l'île Wrangel dans la périphérie du bassin Canada sont particuliers. Les aspects les plus importants sont un magmatisme au Protérozoïque tardif; une orogenèse présumée au Protérozoïque terminal–Paléozoïque précoce; un flysch triasique; une déformation du Chukotkan; et un recouvrement, à la fin du Crétacé précoce, de tous les terranes du nord-est de la Russie par la zone volcanique d'Okhotsk–Chukotsk du Crétacé supérieur.*

## *Summary*

The oldest stratigraphic unit on Wrangel Island is the Upper Proterozoic Wrangel Complex, which outcrops in the central mountains and consists of more than 2000 m of felsic to intermediate volcanic rocks, volcaniclastic rocks, slate/phyllite, minor grey and black slate, quartzite, conglomerate, and very minor mafic volcanic rocks. Wrangel Complex strata are intruded by quartz–feldspar porphyry, gabbro, diabase, and felsite dykes and sills, and small granitic bodies. The sedimentary rocks are probably marine and the tectonic setting of the volcanic rocks remains uncertain. U–Pb zircon dating of Wrangel Complex volcanic and granitic rock has provided crystallization ages of 633 $+21/-12$ Ma and 699 $\pm 2$ Ma, respectively, and a ca. 0.7 Ga on a leuco-granite. The oldest Paleozoic unit on Wrangel Island is a 700 m succession of Upper Silurian and Lower Devonian shallow-marine sandstone, siltstone, slate and carbonate, found only in the northwestern and western parts of the island. These strata are overlain by a 1200 m thick Devonian succession of marginal-marine followed by deep-marine clastic rocks, with conglomerate. In the south of the island this unit directly overlies the Wrangel Complex. In the central mountains Devonian strata are overlain by a 350 m thick succession of Lower Carboniferous, proximally sourced, extension-related, marine and nonmarine clastic rocks, including sedimentary-clast conglomerate, slate, argillite, and minor carbonate and gypsum. This unit is overlain by up to 1400 m of additional Carboniferous strata that include in the northwest, a shallow-water, limestone-dominated facies belt, and in the southeast a transitional limestone and slate belt. Above these strata is a 750 m thick succession of Permian slate and limestone with minor sandstone, coarse clastic rocks and siliceous strata, and in the north, an olistostrome-breccia succession. To the north, Permian strata overstep Silurian to Carboniferous units. These Permian lithofacies range from subaerial deposits overlain by platform carbonates in the northwest, to basin shale and chert in the southeast. Also, in the south-central part of the island, Permian and Carboniferous strata are missing beneath Triassic strata, through either erosion or structural omission. Permian strata are overlain by 800 to 1500 m of Triassic flysch derived from uplifts to the southwest, south and/or southeast that were associated with volcanism.

All rock units of Proterozoic to Triassic age on Wrangel Island were involved in the Chukotkan Orogeny (Middle Jurassic to Early Cretaceous). They were penetratively deformed, and metamorphosed to lower greenschist facies. Typical structures include a pervasive south-dipping cleavage, north-verging folds, thrusts, normal faults and strike–slip faults. Nearly all Chukotkan structures on Wrangel Island can be accounted for in a four-stage, thin-skinned tectonic model. There are multiple detachments throughout the deformed succession but the major ones are in Wrangel Complex slate, Devonian slate and Permian slate. Shortening appears to be at a maximum at the island centre and decreases both east and west. Large depositional basins formed on the continental shelf around Wrangel Island following Chukotkan orogenesis. Only a few tens of metres of postorogenic Paleogene and Neogene clay and gravel deposits are present on Wrangel Island. The youngest stratigraphic unit on the island consists of a few metres of indurated Pliocene mud and gravel, overlain by unconsolidated Quaternary clastic rocks.

Inferred depositional environments, rock composition, isotopes, and structural analysis suggest the following history. Wrangel Island is underlain by Precambrian basement. The oldest documented tectonic event was Proterozoic volcanism and plutonism, followed by inferred early Paleozoic orogenesis, which culminated with substantial uplift and cooling. By the Late Silurian, a stable miogeoclinal facies was established. This facies was replaced in the Devonian by a marginal-marine belt, which in turn was followed by a deep-marine facies. Extensional tectonism, with inferred local uplifts and rift basins, was associated with deposition of Lower Carboniferous strata. Stable-shelf facies conditions were re-established during the remainder of the Carboniferous, with shelf facies in the northwest and basin facies to the southeast. By Permian time, the northwestern part of the island had been uplifted and eroded during a period of renewed rifting, while the southeast remained submerged. By the Late Permian the entire island was inundated, and platform carbonate facies replaced land areas in the northwest, while the southeast continued to submerge. By Triassic time the Wrangel Island area was completely submerged, and flysch from southern highlands associated with volcanism was being deposited. Following the Triassic all rocks

underwent Chukotkan deformation and metamorphism and were subsequently uplifted and deeply eroded. In late Early Cretaceous time, large extensional basins formed in the continental shelf and received thick accumulations of Cretaceous to Tertiary strata, including basalt flows and sills. The Wrangel–Herald Arch was a positive feature at this time. The front of intense Chukotkan-Brookian deformation in Alaska is abruptly offset or deflected right-laterally about 600 km northward to a position north of Wrangel Island. This offset is either a large salient in the orogen and/or due to strike-slip movement.

Some aspects of Wrangel Island's tectonic history in the circum-Canada Basin are peculiar to the Arctic Alaska–Chukotka Ancestral Plate. The most important are: 1) Late Proterozoic magmatic activity and inferred latest Proterozoic–early Paleozoic orogenesis; 2) Triassic flysch deposits, which on the mainland are associated with spilitic basalt and tuff; 3) Jurassic–Early Cretaceous Chukotkan deformation; and 4) late-Early Cretaceous overlap of all northeastern Russian terranes (Arctic and Pacific) by the Okhotsk–Chukotsk volcanic belt. In many tectonic models, the last two postdate or are associated with the formation of Canada Basin.

## *Sommaire*

L'unité stratigraphique la plus ancienne dans l'île Wrangel est le Complexe de Wrangel du Protérozoïque supérieur, qui affleure dans les montagnes centrales et comporte plus de 2 000 m de roches volcaniques felsiques ou intermédiaires, de roches volcanoclastiques, d'ardoise/phyllade, d'un peu d'ardoise grise et noire, de quartzite, de conglomérat et d'une très faible quantité de roches volcaniques mafiques, que recoupent des dykes et des filons-couches de porphyre quartzo-feldspathique, de gabbro, de diabase et de felsite ainsi que de petits massifs granitiques. Les roches sédimentaires ont vraisemblablement une origine marine, mais le cadre tectonique des roches volcaniques demeure incertain. La datation U-Pb sur zircon donne des âges de cristallisation de 633 +21/-12 ma et de 699 ±2 ma, respectivement, pour les roches volcaniques et granitiques du Complexe de Wrangel, et d'environ 0,7 ga pour un leucogranite. Dans l'île Wrangel, l'unité paléozoïque la plus ancienne est une succession de 700 m de grès, de siltstone, d'ardoise et de carbonate de milieu marin peu profond, qui remonte au Silurien supérieur et au Dévonien inférieur et qui se rencontre uniquement dans le nord-ouest et l'ouest de l'île. Ces strates reposent sous une succession dévonienne de 1 200 m d'épaisseur composée de roches margino-marines, puis de roches clastiques abyssales, avec du conglomérat. Dans le sud de l'île, cette unité repose directement sur le Complexe de Wrangel. Dans les montagnes centrales, une succession de 350 m d'épaisseur de roches clastiques marines et non marines d'origine proximale, du Carbonifère inférieur, qui sont associées à l'extension et qui contiennent du conglomérat à clastes sédimentaires, de l'ardoise, de l'argilite et un peu de carbonate et de gypse, recouvre les strates dévoniennes. Elle repose sous un maximum de 1 400 m de strates carbonifères qui contiennent une zone de faciès où prédomine du calcaire d'eau peu profonde, au nord-ouest, et une zone de transition de calcaire et d'ardoise, au sud-est. Au-dessus de ces strates se trouve une succession de 750 m d'épaisseur d'ardoise et de calcaire permiens avec un peu de grès, de roches clastiques à grain grossier et de couches siliceuses et, au nord, une succession d'olistostrome-brèche. Au nord, les strates permiennes recouvrent des unités qui s'échelonnent du Silurien au Carbonifère. Ces lithofaciès permiens varient de dépôts subaériens surmontés de carbonates de plate-forme, au nord-ouest, à du shale et à du chert de bassin, au sud-est. De plus, dans le centre sud de l'île, les strates permiennes et carbonifères sont absentes sous les couches triasiques en raison de l'érosion ou d'une omission structurale. Les strates permiennes sont sous-jacentes à entre 800 et 1 500 m de flysch triasique dérivé de soulèvements au sud-ouest, au sud ou au sud-est qui étaient associés au volcanisme.

L'orogenèse de Chukotkan (du Jurassique moyen au Crétacé précoce) a touché toutes les unités rocheuses du Protérozoïque au Trias dans l'île Wrangel. Ces unités ont été déformées en profondeur et métamorphisées jusqu'au sous-faciès inférieur des schistes verts. Les structures typiques sont notamment un clivage profond à pendage sud, des plis à vergence nord, des chevauchements, des failles normales et des décrochements. On peut représenter presque toutes les structures de l'orogenèse de Chukotkan dans l'île de Wrangel par un modèle tectonique de

couverture à quatre étapes. Des détachements multiples se rencontrent dans toute la succession déformée, mais les principaux se trouvent dans l'ardoise du Complexe de Wrangel, l'ardoise dévonienne et l'ardoise permienne. Le raccourcissement semble avoir atteint son maximum dans le centre de l'île pour décroître vers l'est et l'ouest. De vastes bassins sédimentaires se sont formés sur la plate-forme continentale autour de l'île Wrangel après l'orogenèse de Chukotkan. On ne trouve que quelques dizaines de mètres d'argile et de gravier postorogéniques paléogènes et néogènes dans l'île Wrangel. L'unité stratigraphique la plus récente de l'île comporte quelques mètres de boue et de gravier pliocènes indurés, que recouvrent des roches clastiques quaternaires non consolidés.

Les milieux sédimentaires présumés, la composition des roches, les isotopes et l'analyse structurale révèlent l'histoire suivante. L'île Wrangel repose sur un socle précambrien. Le plus ancien événement tectonique documenté a été une période de volcanisme et de plutonisme au Protérozoïque, suivie d'une orogenèse présumée au Paléozoïque inférieur qui a donné lieu à un soulèvement et un refroidissement importants. Un faciès miogéoclinal stable était en place à la fin du Silurien. Lui a succédé au Dévonien une zone margino-marine qui a donné lieu à un faciès de mer profonde. Une tectonique d'extension, avec des soulèvements locaux et des bassins de rift présumés, est associée au dépôt des strates du Carbonifère inférieur. Des conditions de faciès de plate-forme stable se sont rétablies durant le reste du Carbonifère, avec un faciès de plate-forme au nord-ouest et un faciès de bassin au sud-est. Déjà au Permien, la partie nord-ouest de l'île avait été soulevée et érodée au cours d'une nouvelle période de rifting, tandis que la partie sud-est est demeurée submergée. Au Permien tardif, l'île était entièrement inondée et un faciès de plate-forme carbonatée remplaçait les terres au nord-ouest tandis que la région au sud-est était toujours submergée. Au Trias, la région de l'île Wrangel était complètement submergée, et il y a eu dépôt de flysch en provenance des hautes terres méridionales associées au volcanisme. Après le Trias, toutes les roches ont été touchés par la déformation et le métamorphisme de Chukotkan, puis soulevées et profondément érodées. À la fin du Crétacé précoce, il y a eu formation, sur la plate-forme continentale, de vastes bassins d'extension dans lesquels se sont accumulées des strates épaisses crétacées-tertiaires, y compris des coulées et des filons-couches de basalte. À cette époque-là, l'arche de Wrangel-Herald constituait une forme positive. Le front de la déformation intense de Chukotkan-Brookian en Alaska a subi un décalage ou un détournement dextre d'environ 600 km vers le nord jusqu'à une position située au nord de l'île Wrangel. Ce décalage représente soit une vaste saillie de l'orogène, soit le résultat d'un décrochement, ou les deux à la fois.

Certains aspects de l'histoire tectonique de l'île Wrangel dans la périphérie du bassin Canada sont caractéristiques de la protoplaque de l'Alaska arctique-Chukotka. Les plus importants sont : 1) l'activité magmatique au Protérozoïque tardif et l'orogenèse présumée du Protérozoïque terminal-Paléozoïque précoce; 2) la présence de dépôts de flysch triasiques qui, sur le continent, sont associés à du basalte spilitique et à du tuf volcanique; 3) la déformation de Chukotkan du Jurassique-Crétacé précoce; et 4) le recouvrement, à la fin du Crétacé précoce, de tous les terranes du nord-est de la Russie (Arctique et Pacifique) par la zone volcanique d'Okhotsk-Chukotsk. Selon de nombreux modèles tectoniques, les deux derniers aspects sont postérieurs à la formation du bassin Canada ou y sont associés.

## INTRODUCTION

The arctic regions of northeastern Russia are of special interest to geoscientists. There is substantial evidence suggesting that prior to the Late Jurassic–Early Cretaceous, the present-day Canada Basin may have been much smaller or non-existent. Arctic North America and the Russian Arctic may then have been linked as a single continental mass across this area. In addition, the Canadian and Russian Arctic areas have a high potential for hosting major hydrocarbon deposits. The Alaskan North Slope and Beaufort Sea contain substantial proven reserves. Plate tectonic reconstructions are widely used by industry in evaluating the economic potential of unexplored circum-Arctic regions.

Wrangel Island lies 140 km north of mainland Chukotka and is situated at the juncture of the East Siberian and Chukchi seas (Fig. 1). It represents a unique exposure of Precambrian to Quaternary geology on the 700 km wide Arctic continental shelf of northeastern Russia. For this reason, Wrangel Island was chosen as the first location for co-operative fieldwork in the Russian Arctic under the 1984 Arctic Science Exchange agreement between the governments of the former U.S.S.R. and Canada. This co-operative fieldwork offered the best potential for introducing new constraints on our interpretation of the plate tectonic history of the region.

### Location

Wrangel Island is situated 140 km northeast of Chukotka Peninsula (lat. 71°15′N, long. 179°W), and has an area of 7600 km$^2$ (Fig. 1). It lies 700 km northwest of the Bering Strait, and 350 km northeast of the city of Pevek. Pevek is the nearest settlement accessible by transcontinental airline from Moscow, Magadan, and other Russian cities. The closest adjacent islands on the arctic continental shelf of northeastern Russia are nearby Herald Island, and the New Siberian Islands, the latter situated 1200 km to the west across the East Siberian Sea. Other regional geographical features mentioned in this report are shown in Figures 1 and 2. These include the Chukchi Sea, which extends east of Wrangel Island as far as Point Barrow, Alaska, and Long Strait, which separates Wrangel Island from the Chukotka Peninsula. The continental shelf is approximately 700 km wide in the vicinity of Wrangel Island.

Access to the island is made possible by Aeroflot jet service from Moscow to Pevek, a Au/Sn mining city of approximately 15 000 people located on Chaunskaya (Chaun) Bay off the Arctic Ocean. From Pevek, Aeroflot operates a charter helicopter, and recently, fixed wing service to various small centres, including the village of Ushakovsky on southeastern Wrangel Island (Fig. 2). Ushakovsky is an administrative centre of about 200 people. Also on the island is the village of

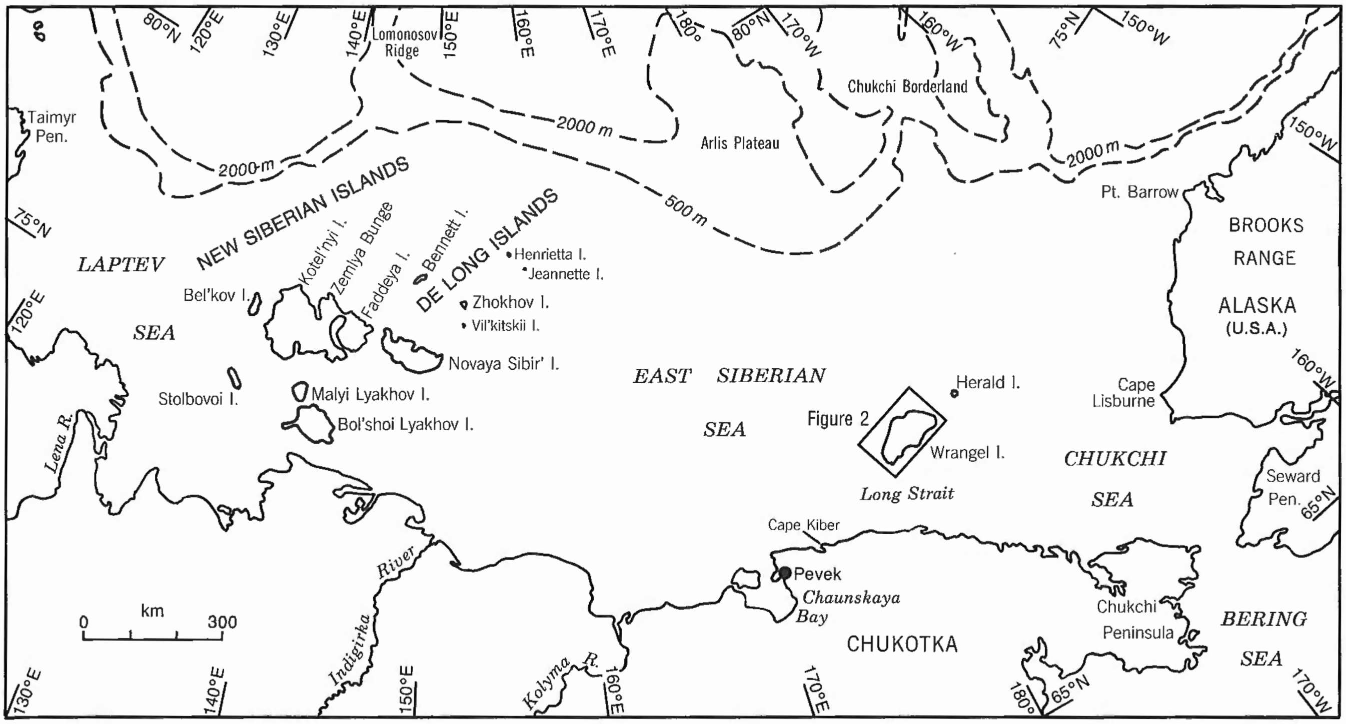


*Figure 1. Geographic features of the East Siberian and Chukchi seas (adapted from Fujita and Cook, 1990).*

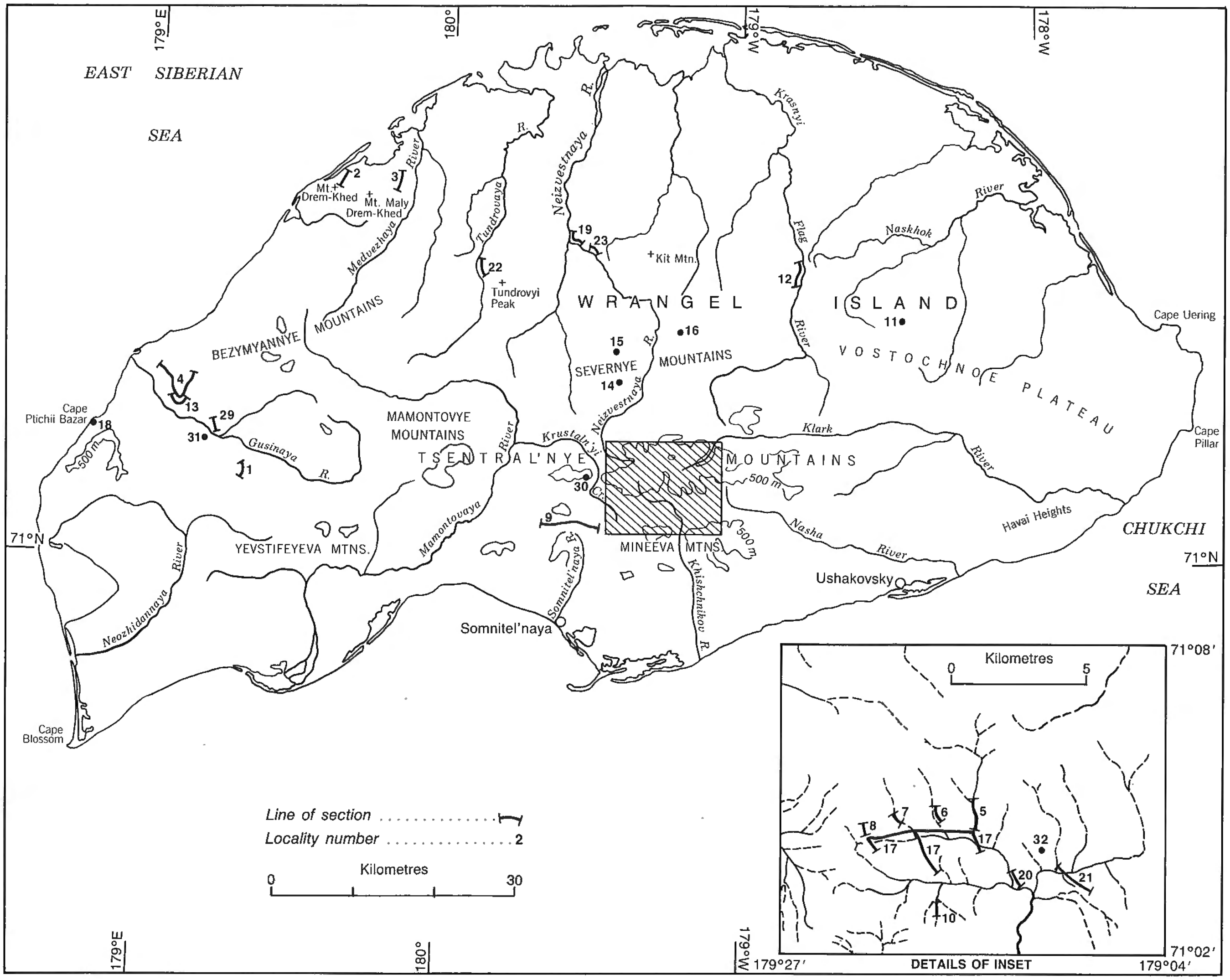


*Figure 2. Locality map of Wrangel Island, showing section locations. Crosshatched area, shown in detail (inset), is the location of Figure 12.*

Somnitel'naya (shown as Zvezdnyi on many maps), which has only a few residents and was used as the base of operation by the Soviet field party. Fly camps and research sites were reached from the base by four-wheel-drive truck.

Geographically, Wrangel Island consists of an up to 15 km wide southern coastal plain (Fig. 3), a broad set of central, low-relief mountains, and an up to 25 km wide northern coastal plain (Fig. 2). The mountainous area is 40 km wide, 145 km long, and trends east–west from coast to coast. The mountains are generally just higher than 500 m. The highest point of land is Mount Sovetsakya (1096 m). The central (Tsentral'nye) mountain range terminates in prominent sea cliffs at either end of the island. The island is dominated by gentle, grass and/or talus covered slopes. The coastal plain dips gently seaward, and appears to be underlain by alluvium.

The island is classified as a natural reserve and access is restricted to administrative and scientific personnel. It is an important Polar Bear denning site, nesting area for some 40 species of birds, and habitat for more than 360 species of vascular plants, 15 of which are reported to be endemic (B. Yurtsev, pers. comm., 1986). Muskox were introduced to the island from herds that originated in the Canadian Arctic. They form a healthy and growing herd that was expected to have reached 60 in number by 1987 (M. Stishov, pers. comm., 1986). Caribou were also introduced to the island. The herd is farmed and kept at a maximum population of about 1000. The most frequently seen wildlife are Arctic foxes and snowy

*Figure 3. The south side of the central (Tsentral'nye) mountains, Wrangel Island. Dark rocks are Triassic strata and light rocks Carboniferous. The coastal plain is covered by Quaternary alluvium. View to the north from the mouth of the Somnitel'naya River. I.S.P.G. photo. 2672-10.*

owls. Coastal sea cliffs at Cape Ptichii Bazar ("Bird Market") and Cape Pillar are the sites of large bird rookeries. Seals and walrus are often seen just offshore.

## Previous work

Wrangel Island was discovered by Captain Thomas Long of the whaling ship the *Nile,* in 1867 (Long, 1867; Vakar, 1970). The first explorer-naturalist on Wrangel Island was J. Muir, a member of an American expedition in 1881 (*in* Hooper, 1884, p. 53, 54; Vakar, 1970). In 1911, I.P. Kirichenko collected some rocks when the icebreaker Vaigach made a brief stop at the island during a hydrographic survey by the Imperial Russian government (Tolmachev, 1912; Vakar, 1970). Detailed geological studies on Wrangel Island date from the 1930s with field studies by L.V. Gromov and M.T. Kiryushina from 1935 to 1940 (Gromov, 1939, 1946, 1947; Gromov and Kiryushina, 1947); fieldwork by members of the "Arctic Explorer Expedition" in the 1950s (Lobanov, 1957); M.E. Gorodinsky in 1960 (Gorodinsky, 1964); S.M. Til'man, S.G. Byalobzhesky, A.D. Chekov and O.N. Ivanov in the 1960s (Til'man et al., 1964, 1970; Ivanov, 1969, 1973; Byalobzhesky and Ivanov, 1971); and K.S. Ageev, N.M. Vasil'eva, G.E. Chernyak and Ya.I. Pol'kin from 1969 to 1972 (Fig. 4; Kameneva and Chernyak, 1973; Vasil'eva et al., 1974; Kameneva, 1975; Chernyak and Kameneva, 1976; Ageev 1979). In his studies, Gromov assigned Triassic and Paleozoic ages to much of the sedimentary rock succession and postulated an early Paleozoic age for the older, more metamorphosed core complex in the centre of the island. Additional studies of Paleozoic stratigraphy were made by Gromov and Kiryushina (1947) and by members of the "Arctic Prospector" expedition of the early 1950s (Lobanov, 1957). Workers on this expedition assumed the presence of Cambro-Silurian, Devonian, and Lower Permian rocks in the Paleozoic part of the succession (Bogdanov and Til'man, 1964). In 1960 Gorodinsky (Gorodinsky, 1964) made important observations on the age of the stratigraphic succession. He inferred that the central complex was Precambrian, and noted that fossiliferous Lower Carboniferous strata rested unconformably on the Precambrian. Gorodinsky also recognized that the Carboniferous strata were unconformably overlain by Upper Triassic sandstone and shale with Carnian and Norian faunas (see review by Bogdanov and Til'man, 1964).

Additional studies in the sixties by Bogdanov and Til'man (1964), Gnibidenko (1968), Til'man et al. (1970) and Ivanov (1973) produced no significant new paleontological discoveries but generated much discussion by their assignment of strata to various Devonian through Permian ages. Based on fieldwork from 1969 to 1972 (see above) Kameneva (1975), Kameneva and Il'chenko (1976), Kameneva and Chernyak (1973, 1975) and Chernyak and Kameneva (1976) recognized Precambrian, Precambrian to Cambrian, Silurian to Devonian, Carboniferous, and Upper Permian successions on Wrangel Island. They also divided Carboniferous strata into members and recognized two different Carboniferous facies belts. Ageev (1979) postulated that a much thicker Middle Cambrian through Upper Devonian succession was present in the central mountains area.

All investigators agreed, at this point, that Wrangel Island is mainly underlain by middle and upper Paleozoic, Triassic, upper Cenozoic and Quaternary sedimentary strata, with small granitic and basic intrusive bodies and some basic and acidic volcanic rocks. The major question then was the age of the central metamorphic complex. Kameneva (1975) and Ageev (1979) argued that rocks exposed in the cores of large anticlines in the centre of the island were Late Proterozoic, whereas Til'man et al. (1964, 1970) and Gnibidenko (1968) hypothesized that the oldest rocks on the island were Devonian to Late Paleozoic in age and their "ancient" appearance was the result of imposed dynamic metamorphism.

The discovery of Devonian fauna by Yu.G. Rogozov (Vasil'eva et al., 1974) initiated an ongoing dispute over the thickness and distribution of

Devonian strata on the island. K.S. Ageev (1979) hypothesized that much of the terrigenous clastic strata outcropping only in the central part of the island were Devonian, and estimated their thickness at about 1500 m. However Kameneva and Chernyak (1973, 1974) showed Devonian strata over very limited area with thicknesses of a few hundred metres.

Prior to fieldwork in 1986, a number of problems were identified as priorities for investigation (Kos'ko, 1986). Specifically, they included: i) the ages of some rock successions; ii) the scale and age(s) of metamorphism and magmatic activity; iii) the style and age of pre-Late Triassic tectonic activity; iv) the age of volcanic rocks; v) the correlation of some stratigraphic

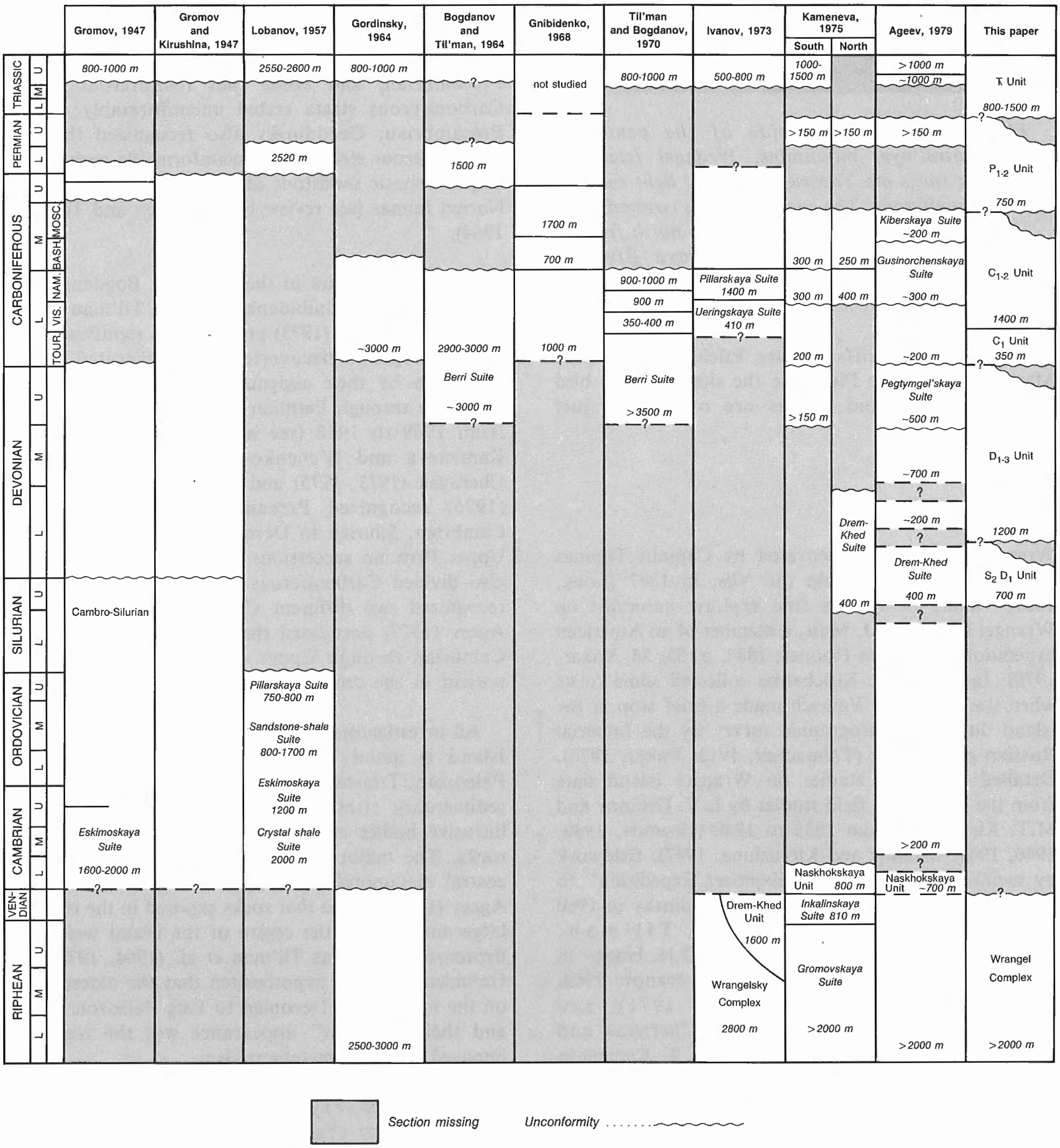


*Figure 4. Stratigraphic nomenclature and correlation on Wrangel Island (modified from Kos'ko, 1986).*

units; and vi) detailed comparisons of the geological history of Wrangel Island with adjacent areas in northern Alaska, the northern Yukon, and the Canadian Arctic Islands. Both Bogdanov and Til'man (1964) and Kameneva (1977) had noted similarity between Wrangel Island and Alaska, particularly with respect to Carboniferous stratigraphy.

In addition to geological studies, extensive geophysical surveys of the surrounding continental shelf have been completed by Soviet and American scientists, including regional gravity and magnetic surveys, and some seismic reflection and refraction work. This information has been succinctly summarized by Kos'ko (1984) for the East Siberian Sea (north and west of Wrangel Island as far as the New Siberian Islands), and by Pol'kin (1984) and Grantz et al. (1975, 1990) for the Chukchi Sea (around and east of Wrangel Island to the Bering Strait). A review of the geology and geophysics of the continental margin north of Chukotka has been recently completed by Fujita and Cook (1990). The neotectonics of Chukotka Peninsula and the East Siberian-Chukchi shelf are discussed by Fujita et al. (1990).

## Recent fieldwork

In the latter half of July, 1986, Canadian scientists joined a Soviet field party led by M.K. Kos'ko for two weeks of traverses in the Tsentral'nye Mountains and west-central coastal areas of Wrangel Island. The purpose of Canadian participation was to see as much of the general geology as feasible, with an emphasis on stratigraphy and structural style. Contacts between various units were examined with a view to understanding Paleozoic and older tectonic events. In addition, sedimentary rocks were sampled for micro- and macro-paleontological analysis, and igneous rocks for U-Pb radiometric dating. Several parallel collections were made by Soviet and Canadian participants to compare results from our respective laboratories.

The visit brought Canadians up-to-date with the new information acquired by the Soviet team working on the island, and the hands-on experience has greatly improved on the ability of all participants to understand geological reports of earlier workers on the island.

A preliminary summary and interpretation was presented by Cecile and Harrison (1987) but has subsequently been changed and improved with new information from additional fieldwork by Soviet authors in 1987 and 1988 (see Ganelin et al., 1989; Kos'ko, Lopatin, and Ganelin, 1990). Detailed subdivision of the upper Paleozoic in some localities on the island was made by V.G. Ganelin and A.V. Matveev. Unfortunately these units cannot be mapped regionally and are not used in this report.

## Acknowledgments

This exchange visit was made possible by the enthusiasm and leadership of the late W.W. Hutchison, former Assistant Deputy Minister, Science and Technology, Energy Mines and Resources, Ottawa, and by I.S. Gramberg, Director General of the PGO "Sevmorgeologia" Vsesoiuznyi Nauchno-Issledovatel'sky Institut Geologii i Mineral'nikh Resursov Mirovogo Okeana (VNIIOkeangeologiya), St. Petersburg, Russia.

We would like to thank L.F. Stashkevich, former Administrative Director of Wrangel Island, for allowing us access to many remote and environmentally sensitive areas.

On Wrangel Island geological assistance was provided by A.V. Matveev and O.N. Vinogradova. Finally we would like to offer special thanks to Y.S. Larianov, a geological pioneer of some 35 years on the Chukotka Peninsula, and to the late L.N. Sutugin, former Director of the Pevek Expedition, who made our stay in Pevek extremely pleasant on our way to and from Wrangel Island.

We would also like to thank the paleontologists at the Geological Survey of Canada, Calgary, and Sylvie Pinard for proofreading the Paleontological Appendix.

# GEOLOGICAL SETTING

## Plate boundaries

The Russian Arctic continental shelf beneath the Chukchi and East Siberian seas, which includes Wrangel Island and the New Siberian Islands, and nearly all of the Chukotka Peninsula, lies within the present-day North American Plate (Fujita et al., 1990; Fig. 6). The North American-Eurasian plate boundary is defined by the Nansen-Gakkel Ridge within the Arctic Ocean Basin. Spreading rates on this ridge decrease progressively from 0.6 cm/yr. near Greenland to 0.2 cm/yr. near the shelf edge of Russia in the Laptev Sea (Grantz et al., 1982). Shallow earthquake foci indicate that the plate margin underlies the shelf of the Laptev Sea and that it emerges on land near the

the Laptev Sea and that it emerges on land near the delta of the Lena River. It then crosses northeastern Russia, where the North American-Eurasian plate boundary is probably contractional as indicated by analyses of earthquake focal mechanisms obtained from this area (Cook et al., 1986). The rotation pole for the North American and Eurasian plates lies nearly on the plate boundary at 71°24′N, and 132°05′E (Cook et al., ibid.). Southeast of Chukotka Peninsula, the North American Plate boundary follows the Aleutian and Kuril-Kamchatka trench systems, where it is in contact with the northwestern edge of the Pacific Plate.

The presently accepted limit of the Arctic Alaska-Chukotka Ancestral Plate, which is tectonically linked to the Canada Basin area, is defined by a discontinuously exposed belt of obducted lower Mesozoic ultramafic rocks (partial ophiolites) that outcrop in the southern Brooks Range of Alaska (Boak et al., 1987; Loney and Himmelberg, 1989) and the South Anyui Suture Zone of the western Chukotka Peninsula (Fig. 5; Seslavinsky, 1979; Cecile et al., 1991b). North of these two ultramafic rock zones there is evidence of continuity of structure and stratigraphy between the Brooks Range, the subsurface of the Alaskan North Slope, and the land and shelf areas of the Chukchi and East Siberian seas as far west as, and including, the New Siberian Islands (Grantz et al., 1981).

## Continental shelves

The East Siberian and Chukchi seas continental shelves include a complex of late Lower Cretaceous-Tertiary basins separated by a variety of positive features (Figs. 5, 6, 7a, 7b, 8). The largest are the North Chukchi/Vil'kitskii, South Chukchi (Hope), Blagoveshchensk, and New Siberian basins, which trend east-west and southeast-northwest. Subsidiary basins are the East Herald and East Chukchi basins and Northern Wrangel Trough. Positive features dividing the basins are the Wrangel-Herald Arch, Medvezhensky Uplift, Anzhu Ridge (a continuation of Wrangel-Herald Arch?), Kotel'nichesko-Svyatonossky High (includes most of the New Siberian Islands), the Gusinsky Uplift, and the North Chukchi Uplift. In addition there are a number of unnamed broad shelf terraces.

Sub-Cretaceous basement consists of deformed Precambrian, Paleozoic and Mesozoic rocks (Kos'ko, 1984; Grantz et al., 1979; Kos'ko et al., 1990; Grantz et al., 1990). Preserved below Cretaceous-Tertiary strata of the Blagoveshchensk and New Siberian Arctic continental shelf basins are sedimentary successions interpreted as Late Proterozoic to middle Paleozoic, late Paleozoic to Middle Jurassic and Late Jurassic to Lower Cretaceous in age (Kos'ko, 1984).

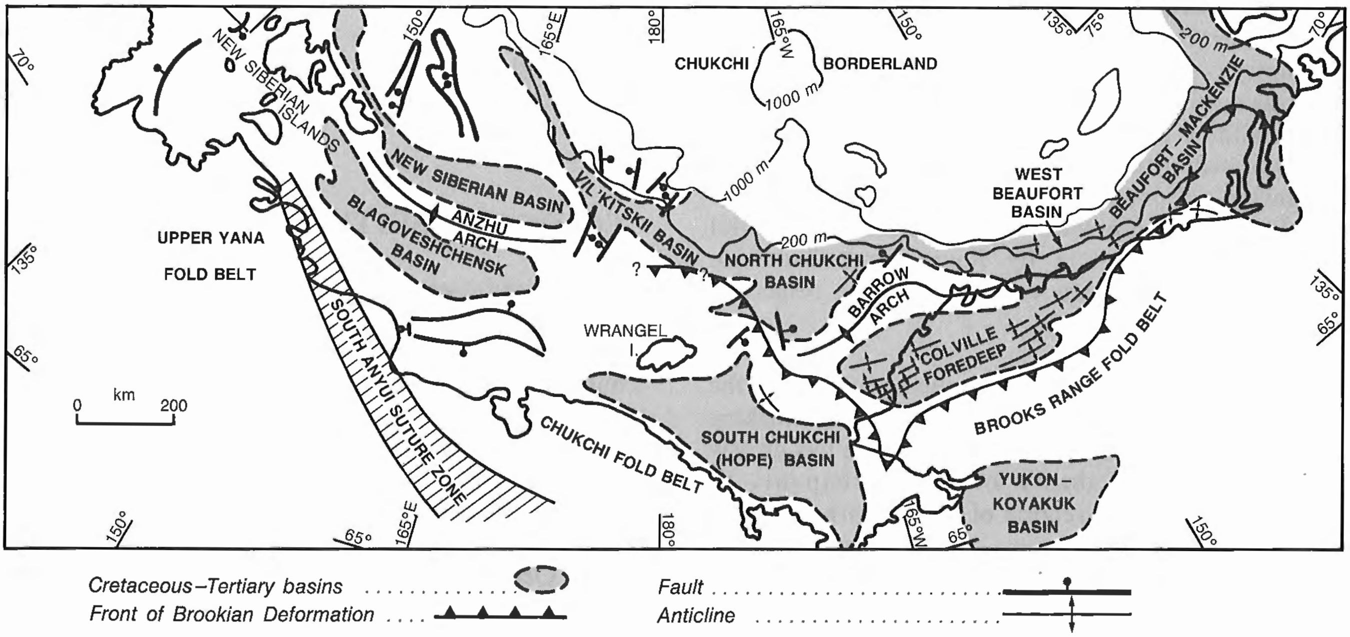


*Figure 5. Major structural elements and Cretaceous-Tertiary basins of the East Siberian, Chukchi and Beaufort continental shelves (compiled from: Grantz et al., 1979; Kos'ko, 1984; Dixon et al., 1985; Fujita and Cook, 1990; Kos'ko et al., 1990).*

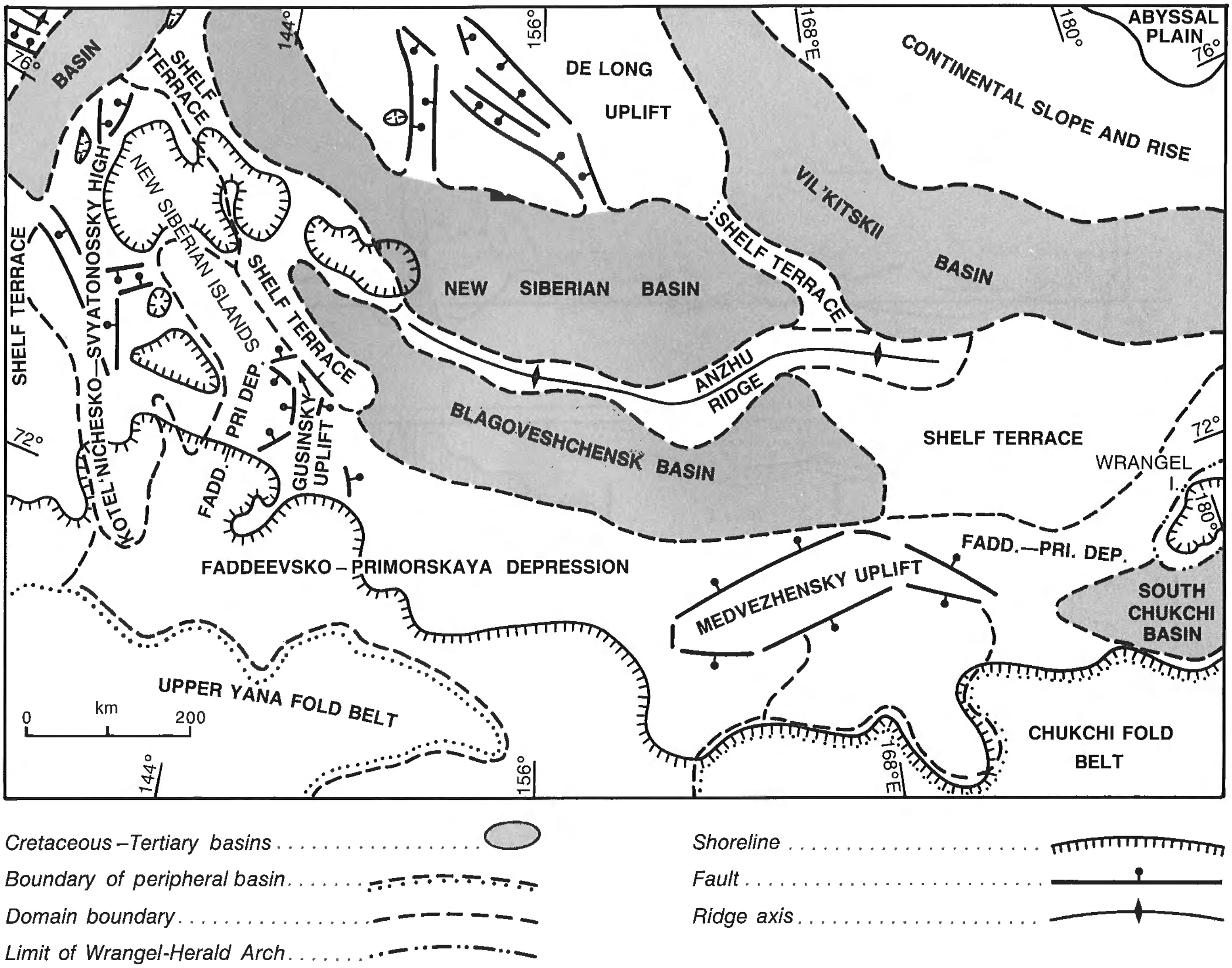


*Figure 6. Structural elements on the continental shelf of the East Siberian Sea (from Kos'ko, 1984, translated by O. Rodkin, 1986).*

## Fold belts

Important structural features of the region are the Brookian (northern Alaska), Chukchi (northern Chukotka, Chukchi Sea and Wrangel Island) and New Siberian (East Siberian Sea and New Siberian Islands) fold belts. These fold belts formed in Middle Jurassic-Early Cretaceous time during Brookian and Chukotkan orogenesis. Cretaceous and Tertiary strata are also mildly deformed by younger compressional and/or extensional events (Grantz et al., 1979; Grantz et al., 1990).

## Brookian-Chukotkan deformation front and the Chukchi syntaxis

An important structural boundary is the front of intense Brookian and Chukotkan deformation. This line was placed by Grantz et al. (1979, Fig. 5) along the front of the Brooks Range in Alaska where it trends westward to the Lisburne Peninsula. Beyond this point, the deformation front turns north and northwestward along the northern boundary of Wrangel-Herald Arch (the Chukchi syntaxis of Tailleur and Brosgé, 1970). It continues on this trend to a position north of Wrangel Island. It has been hypothesized that at this point it turns to the west immediately north of Wrangel Island, because it has generally been accepted that northern Wrangel Island strata are only moderately deformed. However, as we will demonstrate, all rocks on Wrangel Island, north and south, are intensely and penetratively deformed and metamorphosed; therefore, we think that the limit of intense Chukotkan deformation is situated some distance farther north of Wrangel Island than the position established by Grantz et al. (1979; Fig. 5), perhaps at the edge of the continental shelf.

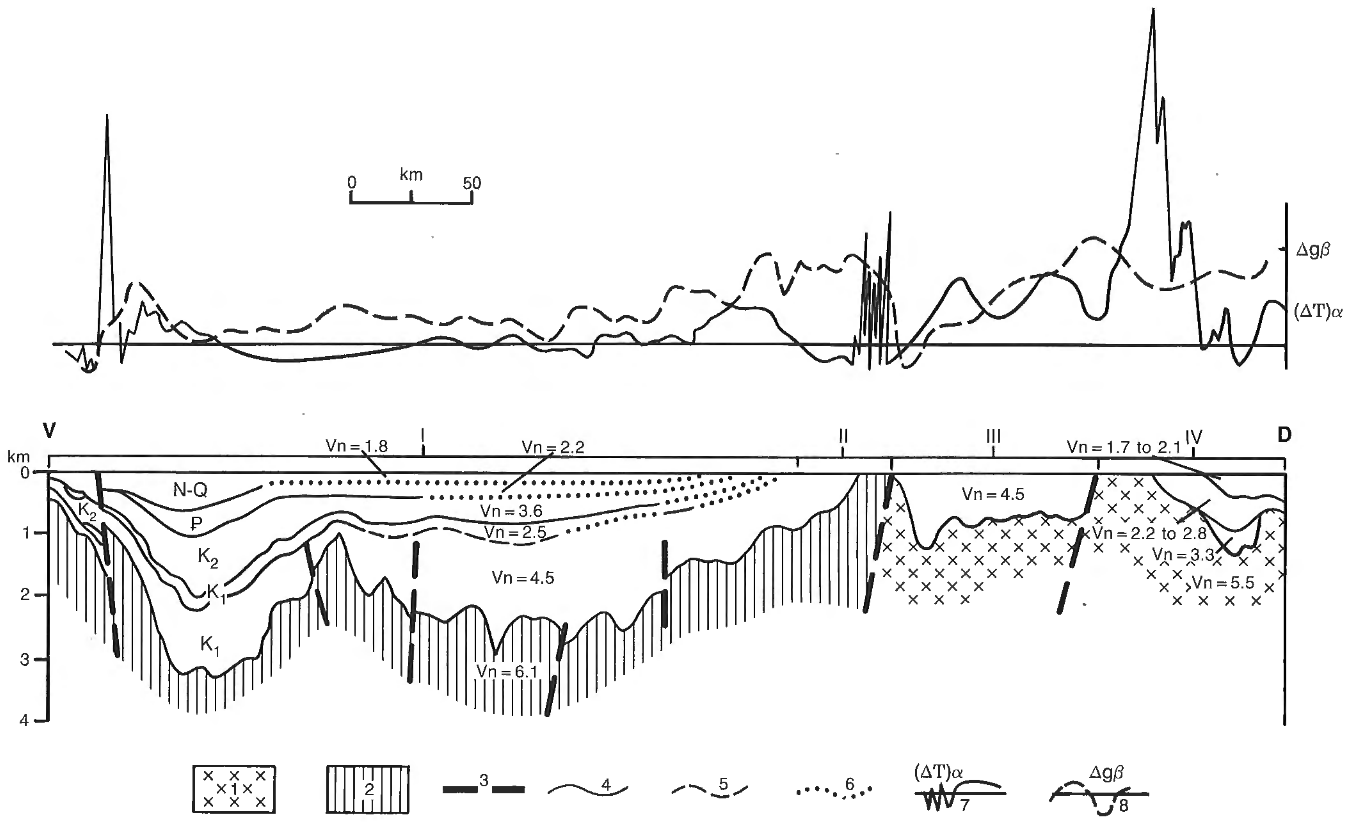


*Figure 7a. Geophysical and interpreted geological profiles across (I) South Chukchi (Hope) Basin, (II) Wrangel-Herald Arch, (III) East Herald Basin, and (IV) Herald Uplift 1. Basement complex of Baikalian (Late Proterozoic) and/or Caledonian (early Paleozoic) age; 2. Basement complex of Kimmeridgian age; 3. Faults; 4, 5, 6, Seismic reflectors – 4 defined, 5 approximate, and 6 assumed; 7. Magnetic profile; 8. Gravity profile $V_n$ = Calculated seismic velocity. See Figure 8 for location (from Pol'kin, 1984; translated by O. Rodkin, 1986).*

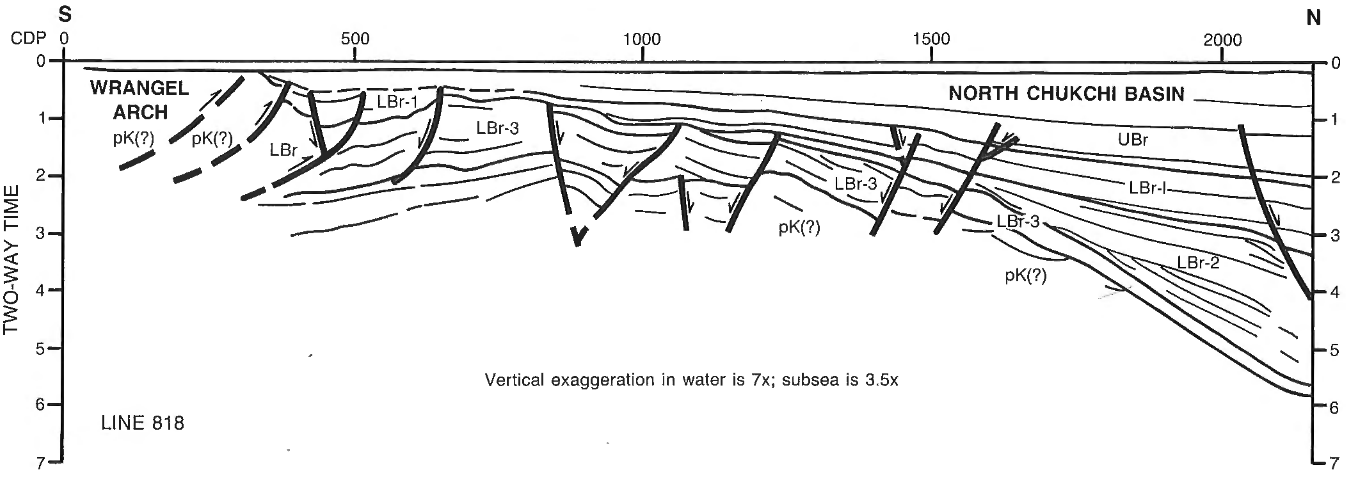


*Figure 7b: Inferred geology on reflection seismic profile 818 across North Chukchi Basin (from Grantz et al., 1990). According to the interpretation of Grantz et al., UBr is upper Tertiary, LBr–1 to 3 are Cretaceous, and pK, pre-Cretaceous. See Figure 8 for location.*

## Wrangel-Herald Arch

Wrangel Island is situated at the western end of the Wrangel-Herald Arch, and although it is considered to be part of Chukchi Fold Belt it is now separated from it by the younger Cretaceous-Tertiary South Chukchi (Hope) Basin (Figs. 5, 6, 8). The Wrangel-Herald Arch trends southeast from Wrangel Island and may link up with north-trending contractional structures of the same age exposed on the Lisburne Peninsula, Alaska.

Similar Jura-Cretaceous foreland highs on trend with, and to the west of Wrangel Island include the submerged Medvezhensky Uplift in the offshore north of the Kolyma River area and the Anzhu Ridge (Fig. 6; Kos'ko, 1984). Because the Anzhu Ridge is a long, narrow feature and partly borders on the North Chukchi/Vil'kitskii Basin, it is the most likely continuation of the Wrangel-Herald Arch.

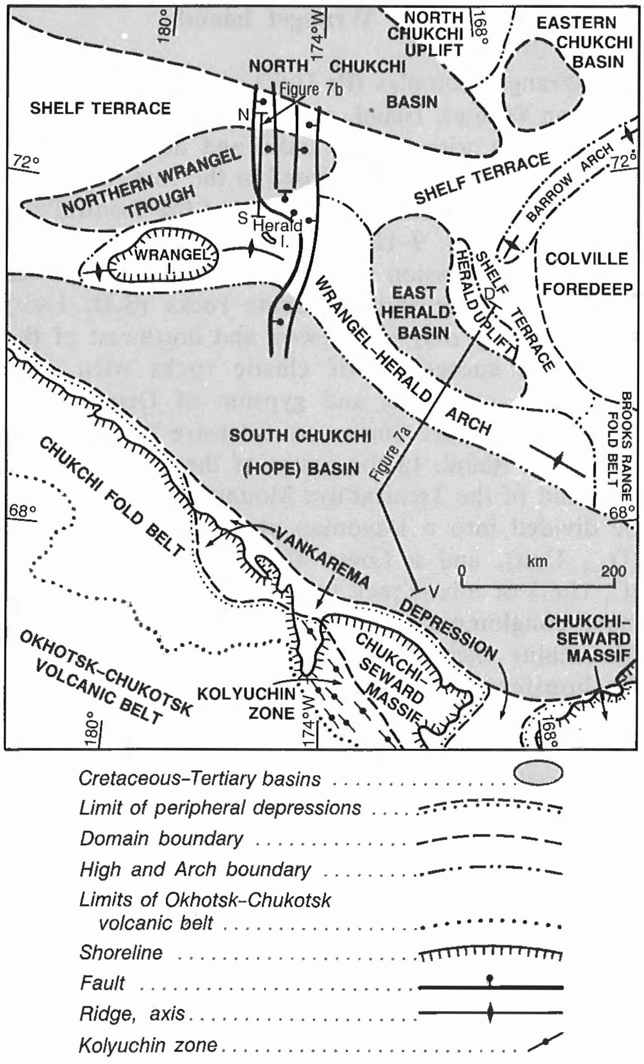


*Figure 8. Structural elements of the continental shelf of the Chukchi Sea. (from Pol'kin, 1984, translated by O. Rodkin, 1986).*

## North Chukchi Basin

On the basis of reflection seismic data, Grantz et al. (1990; Fig. 7b) hypothesized that the North Chukchi Basin is underlain by, in ascending order: i) a succession with three definable seismic stratigraphic units of Cretaceous age that are substantially block faulted, especially in the lower part; ii) a less deformed Cretaceous and/or Lower Paleogene unit; and iii) a Tertiary succession that is mildly faulted in its lower part. The basement on which these successions rest is mostly unknown and labelled pre-Cretaceous, although on the north end of the eastern line it is thought to be upper Paleozoic and Triassic. The lowermost Cretaceous unit on a seismic profile of Grantz et al. (1990) shows thickening toward the Wrangel-Herald Arch, indicating that this feature was a positive element during initial stages of North and South Chukchi basin deposition and thus, at least in part, a postorogenic feature. On a seismic profile north-northeast of Wrangel Island there is a distinct depositional hinge line, north of which all Cretaceous and Tertiary strata rapidly thicken. This indicates that the western North Chukchi and possibly Vil'kitskii basins are shelf edge features over attenuated or transitional continental crust.

## South Chukchi (Hope) Basin

The South Chukchi (Hope) Basin contains a mildly deformed succession that includes up to 4.5 km of low-velocity strata (Fig. 7a). Pol'kin (1984) distinguished five seismic stratigraphic units in the basin, ranging in velocity from 4.5 km/sec. in the lowermost unit to 1.8 km/sec. in the uppermost unit. The postulated age of this succession is Albian to Quaternary. The oldest sequence of Pol'kin has a velocity similar to intervals found in the East Herald Basin, north of the Wrangel-Herald Arch. Because of this Pol'kin (1984) assigned the oldest succession an Albian to Cenomanian age. Following this assumption Pol'kin then hypothesized that the next younger sequences were, in ascending order, as follows: Cenomanian-Turonian (2.5 km/sec.), Turonian-Campanian (3.1-3.6 km/sec.), Paleogene (2.1-2.3 km/sec.) and Neogene-Quaternary (1.8-1.9 km/sec.). Similar strata in the American part of the South Chukchi Basin, the Hope Basin, are interpreted by Tolson (1987) as all Tertiary in age. However

Tolson based his conclusions on extrapolation of seismic data, with well control, from the Kotzebue Basin. The Kotzebue Basin is separated from the South Chukchi (Hope) Basin by a the Kotzebue Arch, making this extrapolation difficult and tenuous. Furthermore, refraction data (Grantz et al., 1975) across the Wrangel–Herald Arch show the stratigraphy of the North and South Chukchi (Hope) basins to be similar, both basins having a lower high-velocity stratigraphic unit (3.1–3.4 km/sec.), indicating a late Early Cretaceous age for the lower unit(s) in the South Chukchi (Hope) Basin in accordance with Pol'kin (1984).

Basement rocks below the South Chukchi Basin (Fig. 7a) have interpreted average sonic velocities of 6.1 km/sec. and 5.2 km/sec., and are interpreted as highly deformed pre-Upper Jurassic rocks (Baikalian and/or Caledonian, Pol'kin (1984; see Figs. 7a, 8). The South Chukchi Basin everywhere sits well south of the Chukotkan–Brookian deformation front. In essence the South Chukchi is basically in an intermontane location, although the only positive area on its northern flanks is the broad Wrangel–Herald Arch which is at least in part a postorogenic feature.

## Magmatism

Magmatism in the Arctic shelf area of northeastern Russia was long lived and variable in its style and geochemistry. In the area of the New Siberian Islands, Fujita and Cook (1990) reported on a variety of volcanic and igneous rocks. These include: on Bol'shoi Lyakov Island, occurrences of Paleozoic or Mesozoic spilite with tholeiitic chemistry; also on Bol'shoi Lyakov, post-Valanginian quartz dolerite dykes, Aptian–Albian granite, granodiorite and diorite and, on both the island and adjacent offshore, talus of peridotite and pyroxenite of late Paleozoic(?) age; on Kotel'nyi Island, post-Devonian diabase-gabbro dikes and sills and post-Triassic diabase dykes; on Bennet Island, Early Cretaceous alkali basalt and Early Cretaceous(?) to Tertiary olivine basalt; on Zhokhov and Vil'kitskii islands, Tertiary alkalic tholeiite and Tertiary(?) nepheline basalt; and finally on Henrietta and Jeannette islands, late Paleozoic tuff, basalt and andesitic basalt.

In the northern Chukchi Sea–mainland Chukotka area, Pol'kin (1984) reported magmatic rocks of Late Proterozoic to Tertiary age. These include: Triassic gabbro and gabbro-diabase sills and dykes intruding Permian and Lower Triassic strata; Cretaceous diorite, granodiorite, monzonite-syenite; and toward the Bering Strait, Cretaceous alkaline syenite and nepheline syenite. Yu. M. Bychkov (pers. comm., 1988) also reported spilite and tuff in mainland Chukotka Triassic strata. Rozenbloom et al. (1987) also showed, on geological maps of the northern Chukotkan coast, successions of Albian to Santonian intermediate and acidic volcanic rocks, which appear to be northernmost extensions of the Pacific epicontinental Okhotsk–Chukotsk Volcanic Belt. Linear, large amplitude, shelf-parallel aeromagnetic anomalies east of the New Siberian Islands and northwest of Wrangel Island are believed to be caused by intrusion of gabbro dykes. The age of these dykes remains uncertain but may be either Late Triassic or Early Cretaceous, or both (Pol'kin, 1984).

## General geology of Wrangel Island

The Wrangel Complex (Pr Unit) comprises the oldest rocks on Wrangel Island, and consists of volcanic and clastic strata with several basic and acidic intrusive bodies. The complex is exposed in the core of a large anticlinorium situated in the centre of the Tsentral'nye Mountains (Figs. 9–11; Table 1). The next youngest unit is a succession of Upper Silurian to Lower Devonian clastic and carbonate rocks ($S_2D_1$ Unit) which outcrop only in the west and northwest of the island. A succession of clastic rocks with conglomerate, carbonate and gypsum of Devonian to Carboniferous age forms an extensive outcrop belt across the island. In the centre of the island and the west end of the Tsentral'nye Mountains, this unit can be divided into a Devonian clastic rock succession ($D_{1-3}$ Unit), and a Lower Carboniferous succession ($C_1$ Unit) of mixed rock types including sedimentary-clast conglomerate and gypsum. In the Severnye Mountains there are small outcrops of probable Carboniferous acidic and basic volcanic rocks (included with generally Carboniferous rocks in Fig. 9). Outcropping extensively in, and north of, the Tsentral'nye Mountains, is a succession of Carboniferous carbonate and slate ($C_{1-2}$ Unit), overlain by Permian slate and carbonate ($P_{1-2}$ Unit). In the north the Permian unit includes a thick olistostrome-breccia complex in its lower part. Forming the flanks of the southern Tsentral'nye Mountains and the core of the Bezymyannye Mountains in the northwest are extensive outcrops of black Triassic clastic strata (Tr Unit). Postorogenic Tertiary and Quaternary strata exposed on the island consist of a few tens of metres of clastic strata. These strata are found on the broad coastal plain in the north of the island. A narrow coastal plain on the south of the island is underlain by unconsolidated Quaternary sediments.

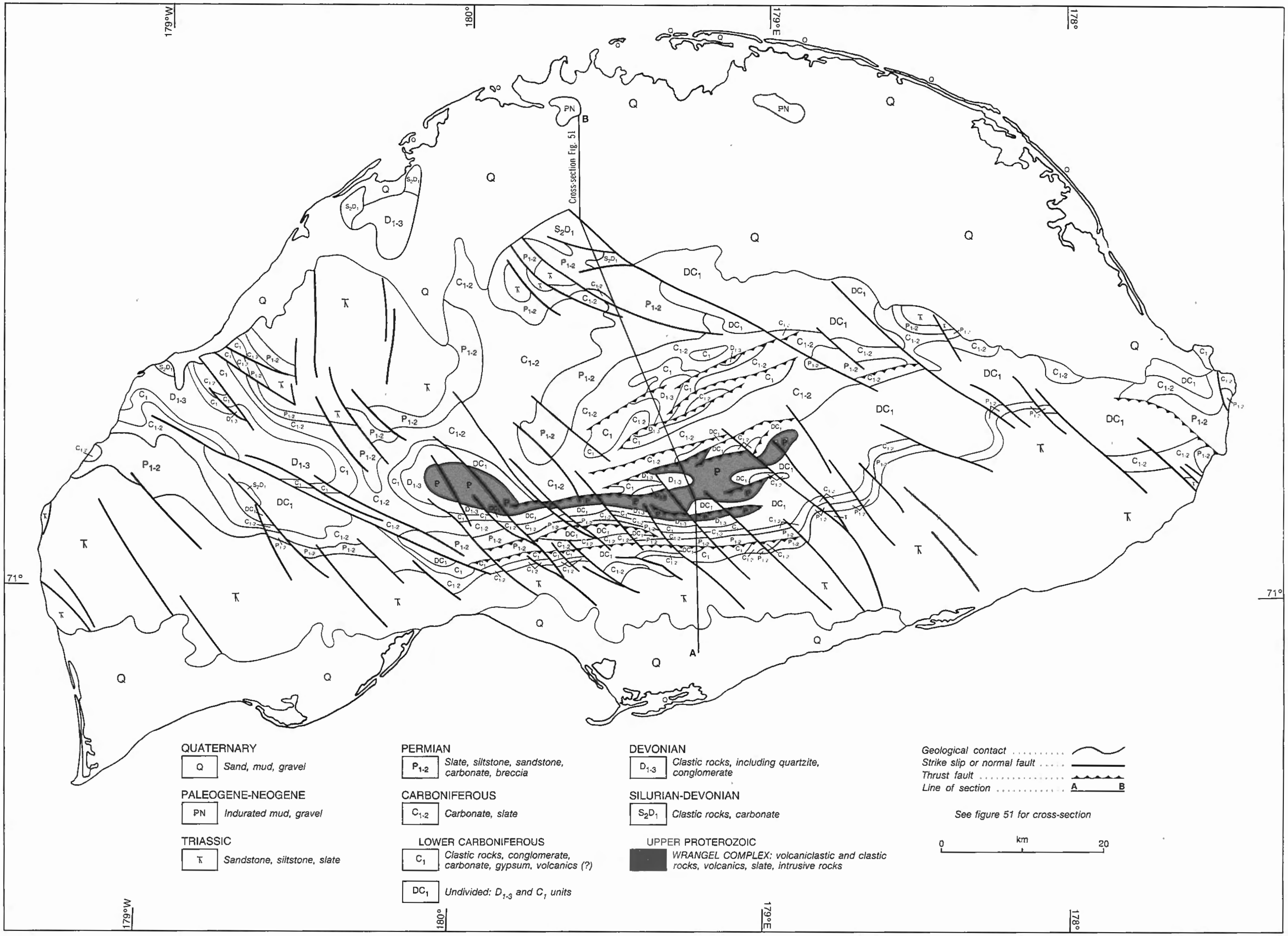


***Figure 9.*** *Simplified geology of Wrangel Island from compilation of Kameneva and Chernyak (1973, 1974). New data from recent fieldwork of M.K. Kos'ko, N.V. Khandozko, V.G. Ganelin, and B.G. Lopatin and unpublished maps of K.S. Ageev (Ageev, 1979).*

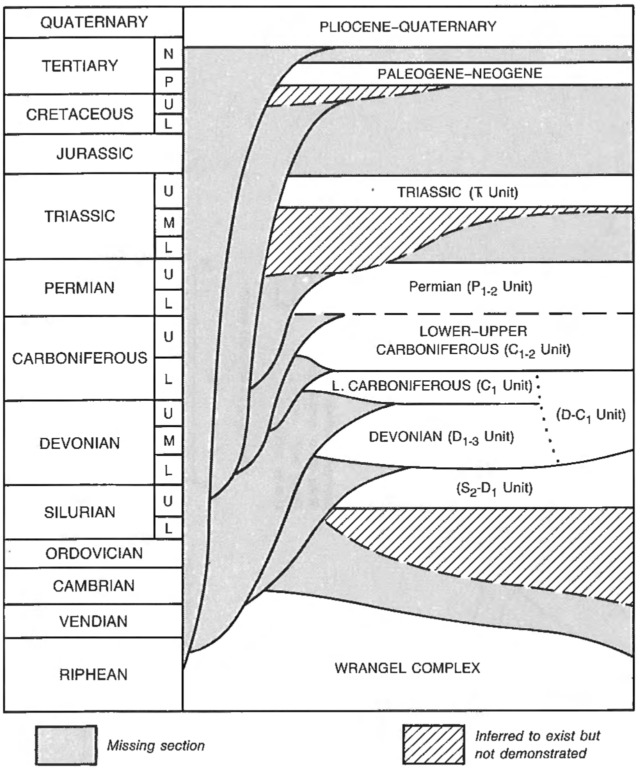


*Figure 10. General stratigraphic scheme.*

Numerous unconformities have been identified or hypothesized on Wrangel Island (Fig. 10). Most apparent on the geological map (Fig. 9) are unconformities marked by: Devonian clastic strata resting directly on Wrangel Complex in the Tsentral'nye Mountains; Permian strata truncating Carboniferous, Devonian and Silurian strata in the north-central part of the island; Triassic rocks in depositional or tectonic contact with Carboniferous and Lower Carboniferous strata in the south Tsentral'nye Mountains; and Tertiary to Quaternary strata on all older rocks.

All Upper Proterozoic to Upper Triassic rocks on Wrangel Island have a pervasive south-dipping slaty cleavage, have been metamorphosed to lower greenschist facies, and were deformed by the Chukotkan Orogeny. Most folds are tight to isoclinal, and folds and thrusts are north vergent. Structural trends are influenced by two large anticlinoria and an intervening synclinorium that vary from east-west to west-northwest and northeasterly (Fig. 9). The youngest structures on the island are northwestly trending faults with small-scale right-lateral strike-slip offsets. There are also a small number of west-northwesterly trending faults with probable normal offsets.

## STRATIGRAPHY

### Wrangel Complex (Pr Unit)

***Definition.*** The name Wrangel Complex was first applied by Ivanov (1969). In this report, the term Wrangel Complex corresponds to the Gromov and most of the Inkalin suites of Kameneva (1975), and to the "metamorphosed" part of the Berri Suite[1] of Til'man et al. (1964, 1970; Fig. 4). Kameneva (1975) and Kameneva and Il'chenko (1976) divided the older "metamorphic complex" of central Wrangel Island into the Gromov and Inkalin suites on the basis of acritarchs, microphytolites and algae. However both formations are lithologically similar and the inferred contact between the two is difficult to recognize, making unequivocal separation and mapping of these units difficult. It is also apparent that part of Kameneva's (1975) and Kameneva and Il'chenko's (1976) Inkalin Suite included strata that we here map and include in the $D_{1-3}$ Unit.

***Type area.*** The type area of the Wrangel Complex is the Tsentral'nye Mountains in the headwaters area of the Khishchnikov River (Fig. 12). The first stratigraphic section was compiled by Kameneva and Il'chenko (1976) in the central part of this area.

***Distribution.*** The rocks of the Wrangel Complex are exposed in an east-west anticlinorium covering the Tsentral'nye and Mamontovye mountains (Figs. 9, 12). They are preserved in a series of overturned north-verging isoclinal folds that comprise the core of the Central Anticlinorium.

***Contacts.*** The lower contact of the Wrangel Complex is not exposed or terminates against faults.

***Composition.*** The Wrangel Complex consists of more than 2000 m of tightly folded and extensively faulted felsic to intermediate volcanic rocks, volcaniclastic rocks, sericitic and chloritic slate/phyllite with minor grey and black slate, quartzite, and conglomerate and very minor mafic volcanic rocks (Figs. 13–16; Appendix 3). Kameneva and Il'chenko (1976) also reported the presence of lenses and beds of "garnet-epidote-diopside marble and marmorized limestone" in this complex. The complex is intruded by small units of quartz-feldspar porphyry, gabbro,

[1]The approximate Russian equivalent of "Formation" is "Suite". However they are not exact equivalents, therefore the term "Suite" will be retained when referring to formal Russian stratigraphic units.

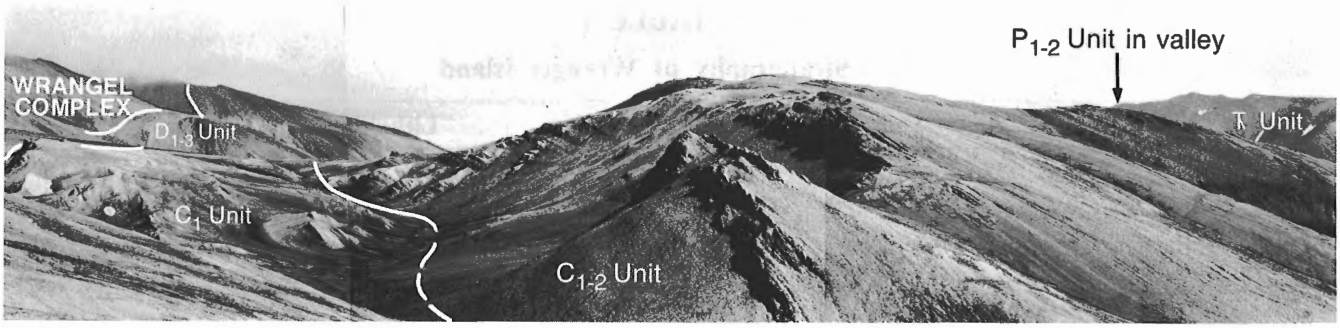


***Figure 11.*** *Panoramic view looking east, of the Tsentral'nye Mountains near the headwaters of the Khishchnikov River. The high mountains on the left (north) enveloped in clouds are underlain by Upper Proterozoic Wrangel Complex. Forming flatirons on the flanks of these mountains are Devonian to Lower Carboniferous clastic strata. In the valley, the light coloured exposures are Lower Carboniferous argillite, sandstone, and gypsum. On the right (south) side of this valley is a Carboniferous succession of limestone and slate exposed on the lower slopes of the mountain in the middle of the panorama. Dark weathering, resistant limestone from the middle part of the Carboniferous succession, offset several hundred metres right-laterally, is well exposed at the top of the mountain (centre foreground). Interstratified limestone and slate from the upper part of the Carboniferous succession underlie the south-facing gentle slope (right-hand side foreground). Triassic strata are exposed on the skyline at the extreme right. Left to right I.S.P.G. photos. 2672-16, 15, and 14.*

diabase, and aplitic felsic dykes and sills, and small, elongate granitic and aplitic intrusive bodies (Fig. 12). All intrusions have been tectonized to some degree. Granitic and basic sills are conformable with compositional layering and are from less than one to fifty metres thick and up to several hundred metres long. Granitic bodies are a few hundred metres thick and may extend for a few kilometres.

A variety of outcrops of the Wrangel Complex in the south part of the Central Anticlinorium illustrates the degree of internal deformation. Some intermediate volcanic rocks contain numerous phenocrysts of quartz and idiomorphic feldspar of apparently primary magmatic origin. Foliation in these rocks was likely primarily caused by extrusive flow during crystallization or compaction of pumice fragments in a hot ash flow deposit (fiamme). In contrast, there are also a variety of less competent phyllitic slates that have lost all evidence of their primary depositional character, except perhaps a relict compositional lamination. Other rocks are essentially porphyritic mylonitic orthogneiss (Fig. 14). These rocks are the product of deformation of primary phenocrysts that were sheared, rotated and partly crushed. In one stream bank exposure of the upper Neizvestnaya River, aplite dykes crosscut compositional layering in the adjacent intermediate volcanic rocks. These dykes are deformed into a series of ductile folds and, in one case, have also been boudinaged. Bogdanov and Til'man (1964) also describe gabbro-diabase sills that have been folded along with the enclosing rocks indicating relatively high strain in some areas.

The high strain in most Wrangel Complex rocks also makes internal subdivision of the unit difficult. Although volcaniclastic rocks appear to structurally overlie various volcanic and hypabyssal-intrusive rocks in sections, this apparent stratigraphic order is nowhere confirmed by tops indicators. Where volcaniclastic rocks and slate structurally underlie volcanic rocks, as is found in the Tsentral'nye Mountains, it is not known whether these rocks occur in their correct stratigraphic position, or on an overturned fold limb. In spite of difficulties in assessing strain magnitude, there appears to be a real difference in the amount of strain of Wrangel Complex rocks in comparison with younger successions.

***Age.*** The earliest attempts to determine the age of the Wrangel Complex were based on microfossils and K–Ar geochronology. On the southern slopes of Mount Mamontovaya, recrystallized limestone yielded microphytolites that indicated a middle Riphean age (Helikian). In addition, microphytolites and algae of Early Cambrian age are known from the same area but it is uncertain whether the host rocks belong to the Wrangel Complex (see Kameneva, 1975; and Appendix 1, Pr–F1). Kameneva (1975) also reported a Late Proterozoic to Early Cambrian age based on acritarchs.

## TABLE 1

### Stratigraphy of Wrangel Island

| Age | Unit | Lithology |
|---|---|---|
| Quaternary | Unnamed | Coarse clastic alluvium, proluvium, eluvium and colluvium. |
| Late Tertiary | Unnamed | Indurated Pliocene mud and gravel (a few metres). |
| Tertiary Paleogene–Neogene | PN | Clay and gravel (a few tens of metres thick). |
| Triassic | Ŧ | Black to dark grey argillaceous quartz turbiditic sandstone with minor feldspar and lithic fragments, black slate; minor siltstone (total thickness estimated to be 800–1500 m). |
| Permian | $P_{1-2}$ | Slate and limestone with minor sandstone, coarse clastic and siliceous strata; in the north the basal part contains a thick olistostrome-breccia succession (up to 750 m thick). |
| Carboniferous | $C_{1-2}$ | Two facies types: 1) microcrystalline and crinoidal biocalcarenite, fine grained, thin bedded limestone, and minor slate and argillite; 2) limestone interstratified with slate and argillite (up to 1400 m thick). |
| Lower Carboniferous | $C_1$ | Clastic rocks, including intrabasinal conglomerate, slate, argillite, with gypsum and carbonate (up to 350 m thick). |
| Devonian | $D_{1-3}$ | Immature clastic rocks, including sandstone, argillite, slate and conglomerate (as much as 1200 m thick). |
| Silurian–Devonian | $S_2D_1$ | Fossiliferous quartzose sandstone, siltstone, slate, carbonate (total thickness = 700 m) |
| Upper Proterozoic | Wrangel Complex | Felsic to intermediate volcanic and volcaniclastic rocks, sericitic and chloritic slate/schist with minor grey and black slate, and very minor mafic metavolcanics, quartzite, and metaconglomerate; intruded by quartz–feldspar porphyry, metagabbro, metadiabase, and aplitic felsic dykes and sills and small elongate granitic and aplitic intrusive bodies (total thickness = >2000 m). |

Previously published K–Ar ages display a wide scatter between 115 and 575 Ma (Firsov, 1966; Ivanov, 1973). These are whole-rock determinations using: $K^{40}$ $\beta$-decay $= 4.68 \times 10^{-10}$ $a^{-1}$ and for $K^{40}$ capture $= 0.585 \times 10^{-10}$ $a^{-1}$ (Firsov, 1966). The oldest ages are 575 and 574 Ma (latest Proterozoic) from a coarse grained granite porphyry, and 513 Ma (Late Cambrian) from a quartz–muscovite–feldspar schist, collected near the west end of the Central Anticlinorium in the same area as samples with U–Pb determinations given below. These ages should probably be considered a minimum, because all igneous rocks in the Wrangel Complex are metamorphosed and more or less deformed. The younger K–Ar ages, which cluster between 420 and 457 Ma (Middle Ordovician to Early Silurian), and between 115 and 224 Ma (Late Triassic to Early Cretaceous) probably represent various events; for example, metamorphic and/or cooling (uplift) ages.

U–Pb ages have recently been obtained from zircons extracted from Wrangel Complex magmatic rocks (Cecile et al., 1991a). All samples were collected from the southern slopes of the Tsentral'nye Mountains. The oldest is a concordant date of 699±2 Ma from a foliated porphyritic granite. A small body of leucogranite gave a younger discordant age of approximately 0.7 Ga. The youngest age was given by a sample of acidic volcanic or subvolcanic rock with a concordant date of 633 +21/-12 Ma. Additional ages were also determined on some of the same samples by S.M. Pavlov and I.M. Vasil'eva (Institute of Geology and Geochronology of the Precambrian, Academy of Sciences, Leningrad). One is a thermionic Pb-Pb zircon date determined to be as old as 590±50 Ma, with a K-Ar muscovite age of 546±35 Ma on the same sample. Muscovite from another granitoid sample gave a 475±31 Ma age. The most reliable ages are the 633 and 699 Ma determinations, which place the Wrangel Complex in the Late Proterozoic.

*Depositional environment.* The abundance of fine grained clastic and volcaniclastic rocks suggests that they were deposited in a subaqueous, probably marine, setting. No substantial accumulations of volcanic rocks

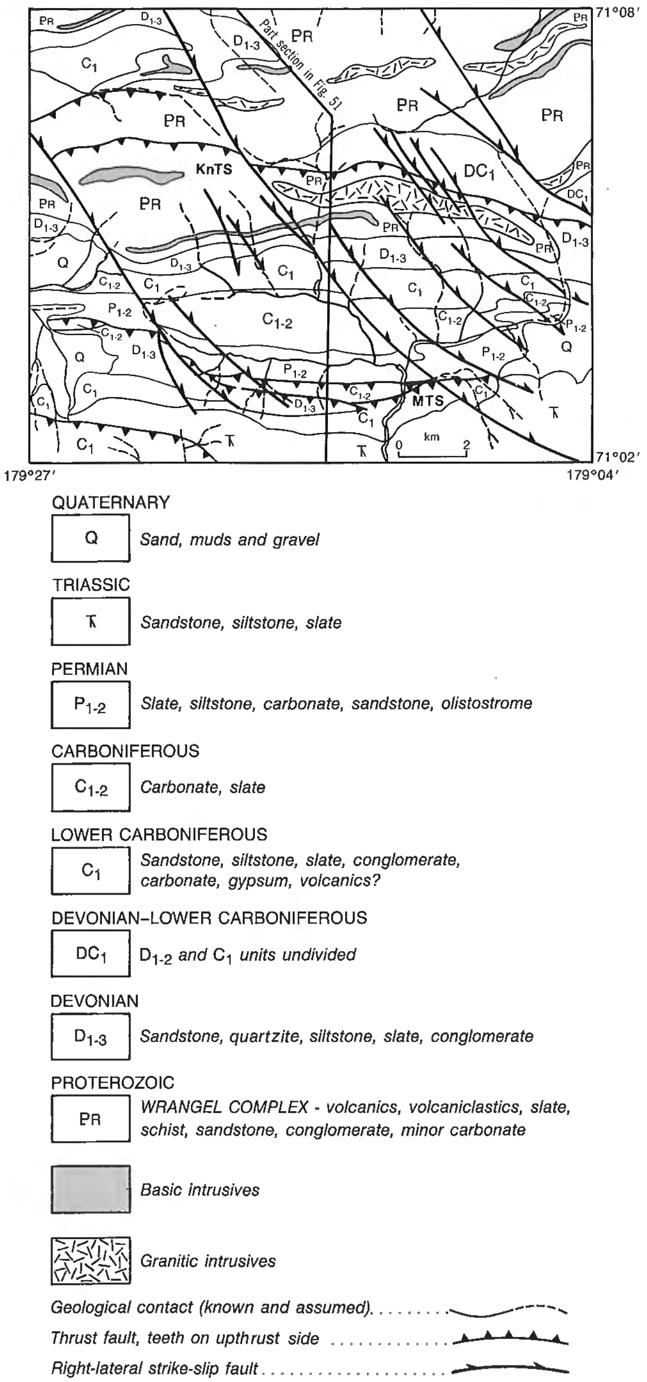


*Figure 12. Detailed geological map of the Tsentral'nye Mountains area. MTS, Mineev thrust sheet; KnTS, Khishchnikov thrust sheet.*

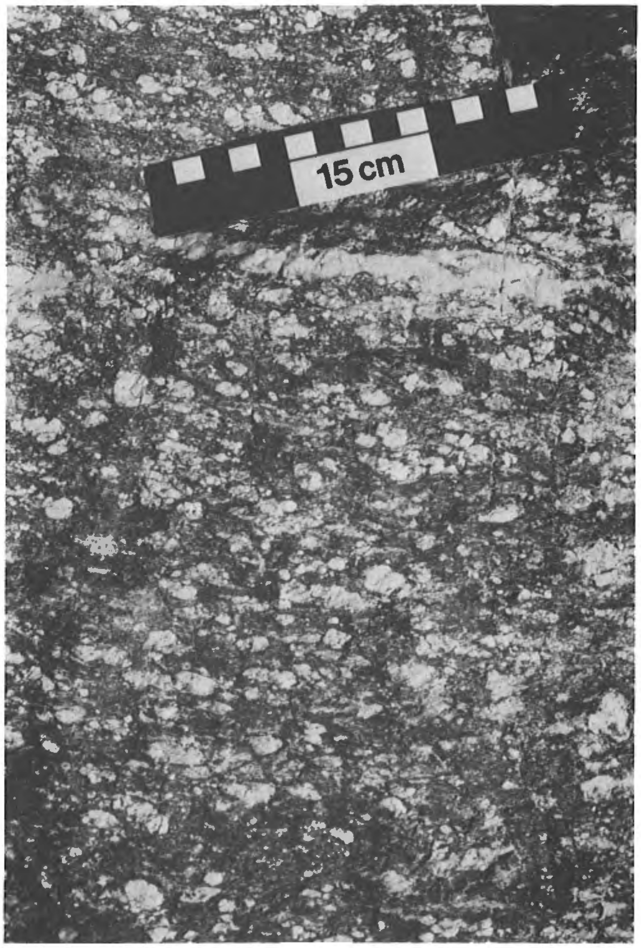


*Figure 13. Foliated porphyritic biotite granite of the Wrangel Complex, from the headwaters of the Khishchnikov River. I.S.P.G. photo. 2672-4.*


*Figure 14. Mylonitic porphyritic orthogneiss, Wrangel Complex from the headwaters of the Khishchnikov River. The phenocrysts have been rotated and tectonic elongated. I.S.P.G. photo. 2672-8.*

*Figure 15. Schistose basic rock, Wrangel Complex, with remnant textures suggesting a mafic fragmental volcanic parent. Sample from the headwaters of the Khishchnikov River. These rocks represent minor components of the Wrangel Complex, and are found in units from less than one metre to several tens of metres thick. I.S.P.G. photo. 2672-20.*

are known indicating no volcanic centres are present within the exposed part of the complex. Although a few geochemical analysis have been made on Wrangel volcanic, intrusive, and mafic rocks (Appendix 3), we consider these data together with our present understanding of range and distribution of Wrangel Complex rocks as too preliminary to assign this complex to a particular tectonic environment.

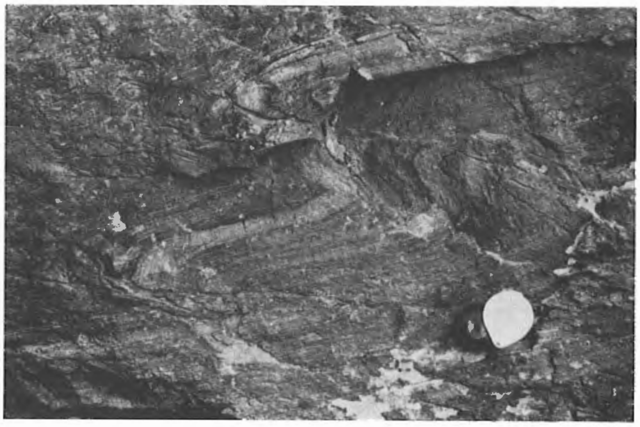

*Figure 16. Minor north-vergent folds and thrusts, volcanic rocks of the Wrangel Complex. This outcrop is situated in the headwaters of the Neizvestnaya River. I.S.P.G. photo. 2672-24.*

## Upper Silurian to Lower Devonian ($S_2D_1$ Unit)

***Definition.*** Upper Silurian to Lower Devonian Unit strata comprise the lower part of a thick succession of mainly Paleozoic clastic strata. Gromov and Kiryushina (1947) and Til'man et al. (1964, 1970) speculated that Silurian and Devonian strata were present on Wrangel Island. This was not confirmed until Silurian and Devonian fossils were identified in 1969 (Vasil'eva et al., 1974), but a stratigraphic unit was not defined. Later Kameneva (1975) defined and mapped an Upper Silurian to Lower Devonian unit that she named Drem-Khed Suite. Her suite was identified in the northwestern part of the island in the Mount Drem-Khed area and a few other nearby localities. Recent fieldwork has delineated a clastic and carbonate succession, at least 700 m thick, of Late Silurian to Early Devonian age, which can be mapped as one unit in the western and northwestern parts of the island ($S_2$-$D_1$ Unit on Fig. 9).

***Reference sections.*** The $S_2D_1$ Unit is clastic dominated on the northwest and carbonate dominated to the southeast (Fig. 18). A reference section for the carbonate facies is at a locality on a southern tributary of the Gusinaya River (Loc. 1, Fig. 2). This stratigraphic section was described by Vasil'eva et al. (1974). This description is considered by us as abnormal because fossil collections reported from the upper beds are older than those from the lower parts of the section, and internal deformation is common. The reference section for the clastic-dominated part of this unit is that described by Kameneva (1975) in the Mount Drem-Khed area, northwest Wrangel island, and our section measured on the slope of Mount Maly Drem-Khed (Fig. 17).

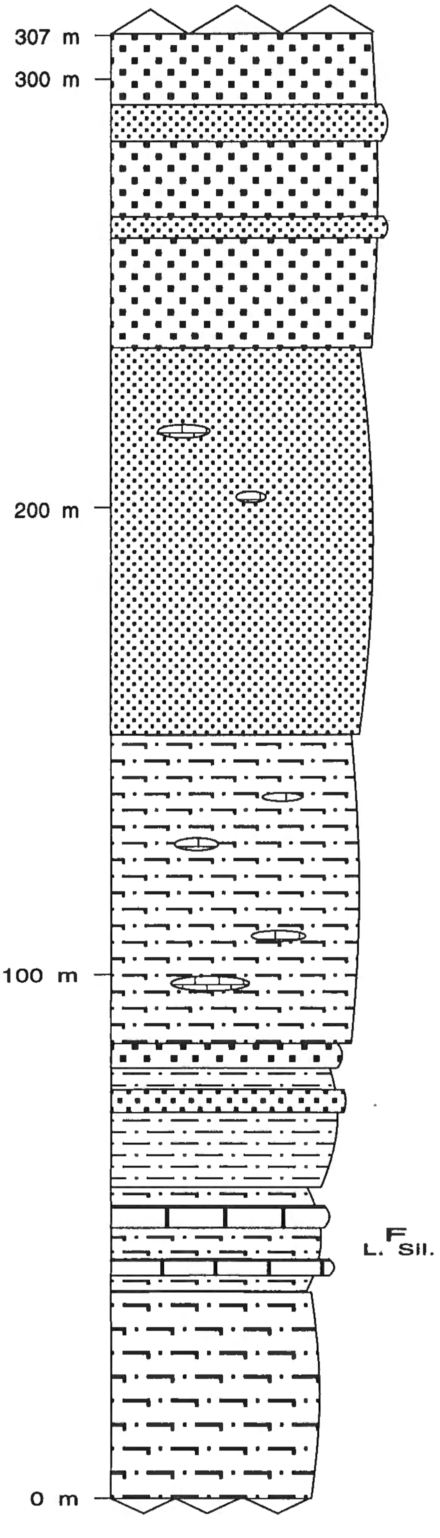


*Figure 17. Stratigraphic section of the lower $S_2D_1$ Unit on the north slope of Maly Drem-Khed. For legend, see Appendix 2.*

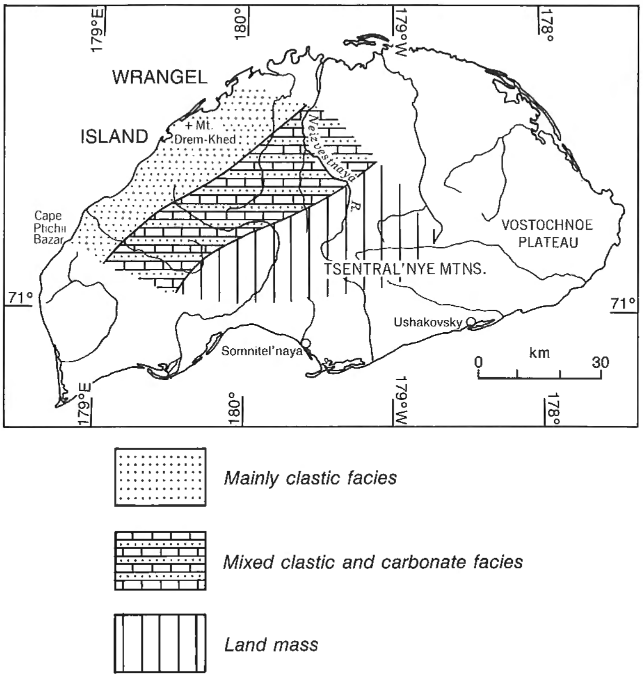


***Figure 18.*** *$S_2D_1$ Unit paleogeography.*

***Distribution.*** $S_2D_1$ Unit strata are found in four isolated localities: i) the northwestern part of the island in the Mount Drem-Khed–Maly Drem-Khed area, where these beds are exposed on the southwest-facing limb of a large south- and southeast-plunging syncline; ii) on the northwestern coast northeast of the outlet of the Gusinaya River; iii) just south of the middle part of the Gusinaya River in the axis of a faulted anticline; and iv) in the middle part of the Neizvestnaya River, where the carbonate part of the succession is exposed in small, anticlinal cores. In the anticlines the $S_2D_1$ Unit carbonates are directly overlain by $P_{1-2}$ Unit rocks.

***Contacts.*** The lower stratigraphic contact of the Upper Silurian to Lower Devonian unit is not exposed. A basal disconformity was identified by Kameneva (1975) between her Drem-Khed Suite and what was assumed to be Cambrian strata in what she interpreted to be an overturned section in the Mount Drem-Khed area. This has not been verified by recent fieldwork. Instead, we interpret the conglomerate described by Kameneva (1975) as a unit from within the younger $D_{1-3}$ Unit, and the stratigraphic sequence as normal.

Upper Silurian to Lower Devonian Unit strata are missing in the central island area, where $D_{1-3}$ Unit strata rest directly on Wrangel Complex.

***Composition and facies.*** In the middle Gusinaya River reference area, this unit consists of alternating 10 to 50 m thick units of limestone, dolostone and clastic rocks. The limestone is blocky- to platy-parted, coarse grained, light grey, dark grey and brownish, crinoidal coral-brachiopod biorudite, and biocalcarenite. The dolostone is light grey, massive and crystalline, and in places contains recrystallized fossils. In some beds the dolostone is interstratified with dark grey bioclastic limestone.

Both types of carbonate are generally brecciated and cut by calcite or quartz-filled veins. Clastic strata are fine grained quartzo-feldspathic sandstone and quartzite, complexly interstratified with siltstone and clay-sericite slate. Most bed forms are thin, parallel or wavy, commonly with small-scale ripples. Clastic units contain some beds of bioclastic carbonate. This middle Gusinaya River succession is estimated to be 400 to 500 m thick.

In the clastic reference area, Mount Drem-Khed, approximately 400 m of the clastic part of the $S_2D_1$ Unit is exposed. Kameneva (1975) described this section as consisting of a succession of thick to very thick beds and units of siltstone and sandstone with minor beds of brachiopod-bearing limestone, shale, grit, and conglomerate containing rounded quartz or quartzite pebbles. The sandstone is predominantly grey to dark grey, fine to medium grained, blocky or platy, and in places thinly bedded. Clasts are predominantly quartz, with 5 to 10 per cent plagioclase, potassium feldspar, quartzite, and rock fragments (quartz-sericite-chlorite-epidote or quartz-biotite schists). The matrix is composed of carbonate and micaceous minerals. The siltstone is grey, and platy, with lenticular or parallel bedding.

V.G. Ganelin and A.V. Matveev (Ganelin et al., 1989) measured a section through the lower part of the $S_2D_1$ Unit on the northern slopes of Mount Maly Drem-Khed (Fig. 17). Here they found about 300 m of grey and green siltstone and calcareous siltstone, fine grained sandstone, and fine to medium grained immature sandstone, with minor beds of bioclastic limestone. Some sandstone units contain crossbeds and ripples. The upper part of the succession in this area has weathered to felsenmeer, and is similar in composition to the lower part just described. The upper part is estimated to be another 400 m thick, for a total thickness of about 700 m.

***Age.*** Vasil'eva et al. (1974) reported Early Devonian corals from collections taken from the reference area in the middle part of Gusinaya River (Appendix 1, $S_2D_1$-F1). Some distance from the above locality Vasil'eva et al. (1974) also reported collecting tabulate and rugose corals containing probable Silurian forms from felsenmeer (Appendix 1, $S_2D_1$-F2).

During fieldwork in 1987, I.M Vasil'eva and M.K. Kos'ko collected tabulate corals from the Gusinaya River area (Appendix 1, $S_2D_1$-F3), most of which suggest an Early Devonian (Lochkovian–Pragian) age, but one specimen may be Silurian. In 1970, G.I. Kameneva and Ya. I. Pol'kin collected a variety of fossils from the Mount Drem-Khed reference area (Appendix 1, $S_2D_1$-F4), which give a probable Late Silurian to Early Devonian age. During fieldwork in 1988, V.G. Ganelin collected fauna similar to the $S_2D_1$-F4 collection as well as additional fauna (Appendix 1, $S_2D_1$-F5), which indicate an age range of late Llandovery to Ludlow, and more likely Ludlow. In addition, he collected a probable Silurian tabulate coral from the middle part of the Neizvestnaya River in the same year (Appendix 1, $S_2D_1$-F6).

On the basis of these data a Late Silurian to Early Devonian age is assigned to this unit. However, because the base of the section is not exposed, the lower age limit cannot be unequivocally determined. The upper age limit is based on a single collection and will likely be refined with further work.

***Depositional environment.*** Two lithofacies are distinguishable in the $S_2D_1$ Unit; one, farthest northwest, comprises mostly clastic rocks and the other, mixed carbonate and clastic rocks (Fig. 18). Both are found in the northwest of the island. The $S_2D_1$ Unit is missing through erosion or nondeposition in the central part of the island. Fossil assemblages and sedimentary structures indicate that both facies are of stable-shelf, shallow-marine origin.

## Lower to Upper Devonian ($D_{1-3}$ Unit)

***Definition.*** Lower to Upper Devonian Unit strata comprise up to 1200 m of mainly sandstone, conglomerate, and slate. Although Gromov and Kiryushina (1947) predicted the presence of Devonian strata, and Vasil'eva et al. (1974) indentified units similar to known Lower and Middle Devonian units found on mainland Chukotka, it wasn't until fieldwork in 1985–86 that the presence of Middle Devonian fossils was documented.

Lobanov (1957) recognized a quartzite unit, his Eskimoskaya Suite resting directly on the "metamorphics" (Wrangel Complex). This quartzite unit was overlain by a sandstone-slate succession, which, in turn, was overlain by his Pillarskaya Suite

(Lobanov, 1957; Fig. 4). He believed all these units were Cambrian to Ordovician in age. Lobanov's Eskimoskaya Suite and his sandstone–slate unit are essentially the lower and upper parts, respectively, of our $D_{1-3}$ Unit mapped in the western part of Wrangel Island. The use of the term Eskimoskaya Suite is not adopted here because the rocks are not regionally mappable, but they are identified as the Eskimo member at some localities. In the Mount Drem-Khed area, the lower part of the $D_{1-3}$ Unit is equivalent to what Kameneva (1975) described as the Naskhok Suite. In the Tsentral'nye Mountains, the $D_{1-3}$ Unit is mappable and equivalent to part of the Inkalin and the lower Naskhok suites of Kameneva (1975). The Naskhok and Inkalin suites are not adopted here because they have been used to describe different units in different areas.

***Reference areas.*** Two principal reference areas have been identified: i) north of the lower Gusinaya River; and ii) the southern slopes of the Tsentral'nye Mountains in the headwaters of the Khishchnikov river, where Lower and Middle Devonian strata vary considerably in lithology and thickness (Fig. 19). Exposure is poor at both localities, but the stratigraphic sections appear to be structurally uncomplicated.

***Distribution.*** $D_{1-3}$ Unit strata outcrop over large parts of western Wrangel Island (Fig. 9). In the Gusinaya River area, these strata outcrop in the cores of broad, northwest-trending anticlines. In the Mount Drem-Khed area, they outcrop on the south-facing limb of a large syncline. In the Mamontovye Mountains, $D_{1-3}$ Unit strata outcrop on the limbs of a large anticline cored by Wrangel Complex, and in the Tsentral'nye Mountains these strata are exposed on the flanks of the anticlinorium cored by Wrangel Complex. Smaller exposures occur in the Neizvestnaya River area within the hinge zones of several small anticlines.

***Contacts.*** In the Mount Drem-Khed area, the lower boundary of the $D_{1-3}$ unit is placed beneath a thick succession of quartz sandstone (Eskimo Member) and above more recessive calcareous siltstone and sandstone of the underlying $S_2D_1$ Unit. The actual contact is not exposed but can be traced in felsenmeer. In the Khishchnikov River area the $D_{1-3}$ Unit rests unconformably on the Wrangel Complex. This contact, exposed in a stream-bank section, is placed at the base of a 50 m thick interval of lensing conglomerate. These beds are clast supported and possess a sparse chloritic matrix. Pebbles and cobbles in the conglomerate are well rounded and include clasts of leucocratic granitoid rocks and subordinate

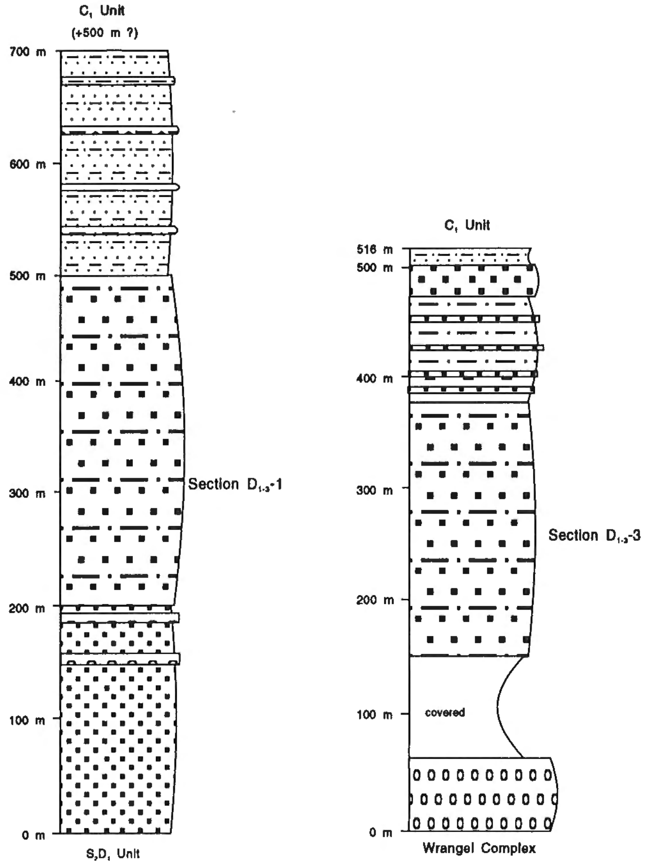


*Figure 19.* *$D_{1-3}$ Unit stratigraphic sections 1 and 3, from the Gusinaya River and Tsentral'nye Mountains, respectively. For legend, see Appendix 2.*

metamorphic rocks similar to those encountered in the underlying Wrangel Complex (Fig. 20). This unconformity and associated conglomerate likely represent a profound tectonic event in the geological history of Wrangel Island.

***Composition.*** In the reference area, north of the Gusinaya River, the lower half of the $D_{1-3}$ Unit consists of conglomeratic coarse grained quartzite, 150 to 200 m thick. Pebbles and cobbles are scattered through these beds but also occur more commonly in discrete discontinuous lenses. Also in this lower section, granule-rich sandstone ("gritstone") and small-pebble conglomerate are increasingly abundant in the higher beds. Clasts are dominantly vein quartz. However, rare clasts of feldspar-bearing chloritic slate of probable acidic volcanic origin are also present. This lower unit is essentially the Eskimoskaya Suite of Lobanov (1957), and is equivalent to our Eskimo Member. This lower half of the $D_{1-3}$ Unit is overlain by approximately 300 m of fine to coarse grained, immature sandstone with lesser siltstone and slate,


*Figure 20. Basal conglomerate of the $D_{1-3}$ Unit exposed on the upper Khishchnikov River. Clasts consist of quartzite and foliated leucogranite, typical of the underlying Wrangel Complex. I.S.P.G. photo. 2672-7.*

displaying soft sediment folds. This in turn is overlain by a very thick, recessive interval of fine grained, immature slaty sandstone and slate containing thin beds of siltstone, and thick units of black cherty slate and quartzite (Fig. 19).

In the Mount Drem-Khed reference area, the $D_{1-3}$ Unit consists of a 300 to 350 m thick lower interval of variably greenish grey and pink-grey quartzite with fewer beds of red argillite and calcareous argillite. These distinctive rocks are in turn overlain by an upper interval of black slate and well-sorted, fine to medium grained lithic sandstone. The contact between the lower and upper intervals is not exposed and the thickness of the upper interval is unknown (Appendix 2, $D_{1-3}$ Section 2).

In a section measured on the southern slopes of the Tsentral'nye Mountains, the $D_{1-3}$ Unit is up to 516 m thick (Fig. 19). At the base of this section is a well-exposed conglomerate; above is a complex succession of quartz sandstone, feldspathic and argillaceous sandstone, and argillite with lesser conglomerate and cherty siltstone. Eighty per cent of clasts in the 50 m thick basal conglomerate resemble rocks typical of the Wrangel Complex.

The lower part of the $D_{1-3}$ Unit, encountered in a traverse section near the west end of the Tsentral'nye Mountains, is intermittently exposed through talus-covered slopes and blocky felsenmeer. The basal contact with the Wrangel Complex is covered, and the $D_{1-3}$ succession is divisible into three units. The lowest is a resistant, ridge-forming interval approximately 250 to 300 m thick that includes unsorted, highly immature, clast-supported conglomerate and breccia in the lower part. Clasts in these beds comprise grey slate and greenish slaty argillite of volcanic or volcaniclastic origin. These beds appear to grade upward into granule and pebble conglomerate displaying variably rounded clasts of quartz with lesser chloritic slate (Fig. 21). The medial unit is a recessive interval, some tens of metres thick, that includes interbeds of light brown dolostone, green slaty argillite, thin beds of light brown weathering sandstone and pebbly sandstone, and lenses of polymict clast-supported conglomerate. The conglomerate contains well-rounded clasts of quartzite, slaty argillite, vein quartz, and leucogranite. Brachiopods of Devonian age occur in the dolostone beds. The stratigraphic relation amongst these various rock types remains uncertain, because the strata are only exposed in talus boulders and blocks. The highest unit (estimated 20 m) is a ridge-forming exposure of coarse grained quartz sandstone locally displaying large-scale trough cross-stratification (Fig. 22). The upper part of the $D_{1-3}$ Unit in this area is covered and the thickness of beds beneath the $C_1$ Unit is unknown.

In the Tsentral'nye Mountains, in the area of the Somnitel'naya River headwaters, an exposure of the upper part of the $D_{1-3}$ Unit consists of the following. At the base of the exposure is a more than 200 m thick unit of 90 per cent dark green, micaceous, usually calcareous, fine grained, commonly parallel-laminated and slump-folded sandstone (Fig. 23) and silty sandstone with very thin argillite beds. This unit is overlain by a succession of thin bedded, argillaceous sandstone and arenaceous/argillaceous limestone, the limestone tending to be more abundant higher in the succession.

*Figure 21. $D_{1-3}$ Unit granule and pebble conglomerate displaying variably rounded and flattened clasts of quartz with lesser chloritic slate, western Tsentral'nye Mountains. I.S.P.G. photo. 3819-3.*

*Figure 22. Large-scale trough crossbeds in $D_{1-3}$ sandstone unit. I.S.P.G. photo. 2672-21.*

*Figure 23. $D_{1-3}$ Unit parallel-laminated and slump-folded sandstone. I.S.P.G. photo. 3819-2.*

On the east side of the central Khishchnikov River is a more than 170 m thick succession of the upper $D_{1-3}$ Unit consisting of sandstone, siltstone and slate in about equal amounts (Appendix 2, $D_{1-3}$ Section 4). Most of the strata in this succession are black or grey, and the slate in the lower third is siliceous. This succession is overlain by Tr Unit clastic rocks.

In the headwaters area of the Neizvestnaya River, only the upper part of the $D_{1-3}$ Unit is exposed in the cores of anticlines. Here it consists of a monotonous succession of unfossiliferous black slate and slaty siltstone overlain by polymict conglomerate assigned to the $C_1$ Unit.

In the area of Krustal'nyi Creek on the north slopes of the Tsentral'nye Mountains, there are large boulders of conglomerate, which are only found in felsenmeer. The size and re-occurrence of these boulders in an unglaciated area suggest that they are from the underlying $D_1C$ Unit (undivided $D_{1-3}$ and $C_1$ units). The compositions of the conglomerates suggest they are likely from the $D_{1-3}$ part of this undivided unit. These conglomerate boulders contain foliated granitic clasts with the foliation in various orientations (Fig. 24). These conglomerate clasts, along with other evidence (see Tectonic history) are critical in documenting a lower Paleozoic deformational event.

***Age.*** Givetian brachiopods have been recovered from the south slopes of the Tsentral'nye Mountains at approximately 250 to 300 m above the base of the $D_{1-3}$ Unit (Appendix 1, $D_{1-3}$-F1).

The presence of foraminifers from the genera *Nanicella* and *Tikhinella*, recovered from $D_{1-3}$ Unit strata in the Cape Ptichii Bazar area and the headwaters area of the Somnitel'naya River, indicate Late Devonian, probably Frasnian ages (Rogozov et al., 1971; see Appendix 1, $D_{1-3}$-F2). The genus *Nanicella* is known from Frasnian strata of the Russian Platform, Urals, Belgium, and northwest Australia, and is found throughout the Upper Devonian in the U.S.A. and Canada. All forms of the genus *Tikhinella* have been extracted from Frasnian strata of the Russian Platform and the Urals.

The bracketing age range of the $D_{1-3}$ Unit is probably Emsian through Frasnian but it may also be slightly older or younger.

*Figure 24. Large boulder found within the outcrop area of the $DC_1$ Unit. Conglomerate clasts consist of various leucocratic to mafic gneisses and porphyritic gneisses similar to those found in the Wrangel Complex. Note that the boulder-size clasts display tectonic fabrics in different orientations. I.S.P.G. photo. 2672-18.*

***Depositional environment.*** Devonian strata show both normal and graded bedding, slump folds, soft-sediment slump structures, and trough-crossbedding. Coarse grained marginal-marine strata are abundant in the lower part of the succession and are replaced upward with fine grained, deep-marine strata. In strata above the conglomeratic lower half there is an upward decrease in compositional maturity, and rare sand grains of acidic volcanic origin or probable acidic volcanic origin have been identified.

The environmental setting could be characterized as initially marginal marine, with transgression eventually blanketing the central Wrangel Island area. Higher strata are considered shelf submarine.

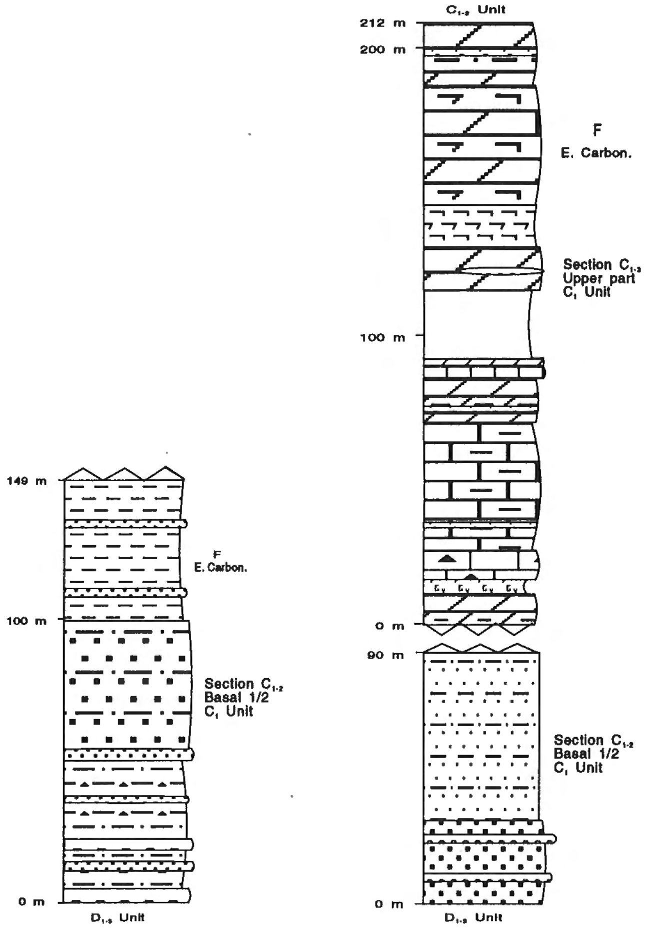


*Figure 25. Stratigraphic sections from the $C_1$ Unit type area, Khishchnikov River. For legend, see Appendix 2.*

## Lower Carboniferous ($C_1$ Unit)

***Definition.*** The Lower Carboniferous ($C_1$ Unit) consists of up to 350 m of clastic strata, including distinctive conglomerate, and carbonate rocks with minor gypsum. The succession rests disconformably on the Devonian ($D_{1-3}$) Unit, and is conformably overlain by Lower to middle Carboniferous $C_{1-2}$ Unit strata. Over much of the island the unit cannot be differentiated from Devonian strata without detailed mapping, and in these places the two are mapped together as the Devonian–Lower Carboniferous ($DC_1$) Unit.

Various names and ages have been applied to parts or all of this unit during previous reconnaissance studies of the island (Fig. 4). The Berri Suite (Bogdanov and Til'man, 1964; Til'man et al., 1970), the Pegtymel Suite together with lower member of the Yunona Suite of Rogozov et al. (1971), and "Tournaisian–Viséan" and Upper Devonian strata of Kameneva (1975) all essentially describe this unit. The Pillarskaya Suite of Ivanov (1973), from near the headwaters of the Somnitel'naya River, and the Naskhok Suite of Kameneva (1975) and Kameneva and Il'chenko (1976), in the upper Khishchnikov River area, both belong in the lower part of the $C_1$ Unit.

***Type area.*** The type area for the $C_1$ Unit is the headwaters of the Khishchnikov River. In this area a complete composite section has been assembled from exposures along various tributaries to the main river (Fig. 2, Locs. 5–8), using local marker units (Fig. 25). In the type area, the $C_1$ Unit can be divided into a lower clastic succession dominated by argillite and sandstone with units of immature conglomerate and breccia, and an upper carbonate-dominated succession with minor units of clastic strata and gypsum. The conglomerate and breccia in the lower part are regionally characteristic in that they form both thin and thick beds and units, and are composed predominantly of phyllite and sandstone clasts that are transected, along with the matrix, by regional slaty cleavage and appear to be highly flattened.

***Distribution.*** The $C_1$ Unit can be mapped as a distinct unit in the Bezymyannye, Mamontovye, Tsentral'nye and Mineeva mountains (Fig. 2). In particular, it outcrops around a large anticline in the Bezymyannye Mountains, north of the Gusinaya River. In the Mamontovye Mountains, a succession interpreted as the $C_1$ Unit outcrops on the south limb and nose of an anticline cored by Wrangel Complex. On the north slopes of the Mineeva Mountains the $C_1$ Unit is found above the upper $D_{1-3}$ Unit in the hanging wall of a north-directed thrust. Along the south slopes of the Tsentral'nye Mountains it can be mapped from the headwaters of the Khishchnikov River west to the Khrustal'nyi Creek area on the south limb of the Central Anticlinorium. In the upper Neizvestanaya River basin it forms most of the hinge-area sections within several faulted anticlines.

Elsewhere on the island it is difficult to differentiate from older clastic strata, and the $C_1$ Unit and $D_{1-3}$ Unit strata have been mapped as a single unit ($DC_1$).

***Contacts.*** The $C_1$ Unit rests disconformably on Devonian strata. This contact was observed on a headwaters tributary to the Khishchnikov River (Loc. 5, Fig. 2). Here a bed of conglomerate and coarse grained sandstone forms the basal unit of the Lower Carboniferous succession, and directly overlies a siliceous chloritic slate of the $D_{1-3}$ Unit. Similar thin units of conglomerate are found higher in the same section.

Although the lower contact surface shows no evidence of substantial erosion, the presence of local units of immature conglomerate and breccia (with dominantly phyllite and sandstone and minor quartz and carbonate clasts) indicates substantial change in the depositional setting.

Elsewhere the presence of conglomerate with phyllite, sandstone, quartz and carbonate clasts is critical in defining the basal part of the $C_1$ Unit. Usually the conglomerate is a substantial unit, but on the north slopes of the Mineeva Mountains, close to and on either side of the Khishchnikov River, only a few thin beds of pebble conglomerate were found, along with crinoidal limestone, at and above the boundary between the $D_{1-3}$ and $C_1$ units.

***Composition.*** In the type area, the upper Khishchnikov River, a composite of the $C_1$ Unit can be assembled (Fig. 25). The lower part is multicoloured (maroon, green, brown), 150 m thick and consists of, in ascending order: a unit of conglomerate, a very thick succession of green argillite with minor sandstone and conglomerate, a very thick unit of sandstone with minor slate and siltstone (Fig. 26), and finally, a very thick succession of greenish grey slate with rare sandstone (Fig. 27). The upper part of the unit is recessive, light coloured, 140 m thick, and consists of, in ascending order: a unit of (predominantly) dolomite, a thin unit of white gypsum, a unit of massive limestone, a thick unit of platy argillaceous limestone with gypsum, a thick unit of dolomite with gypsum, a thin unit of platy limestone, a thick unit of dolomite with minor terrigenous conglomerate, a thick succession of dolomitic mudstone, a very thick succession of dolomite and dolomitic and calcareous mudstone, and finally, a very thick unit of silty claystone and gypsum (Figs. 25, 28, 29).

Farther west in the Tsentral'nye Mountains, at the headwaters of the Somnitel'naya River, the $D_{1-3}$ Unit is conformably overlain by an 80 to 160 m thick upper unit of green, phyllitic, pebbly argillite, calcareous pebbly argillite and conglomerate (Fig. 30). Pebbles are locally derived and consist of angular slate and sandstone and minor pebbles of vein quartz and pinkish red carbonate. Minor thin beds of buff-red weathering calcareous sandstone, with rare corals, in talus, are found in the upper part of this unit.

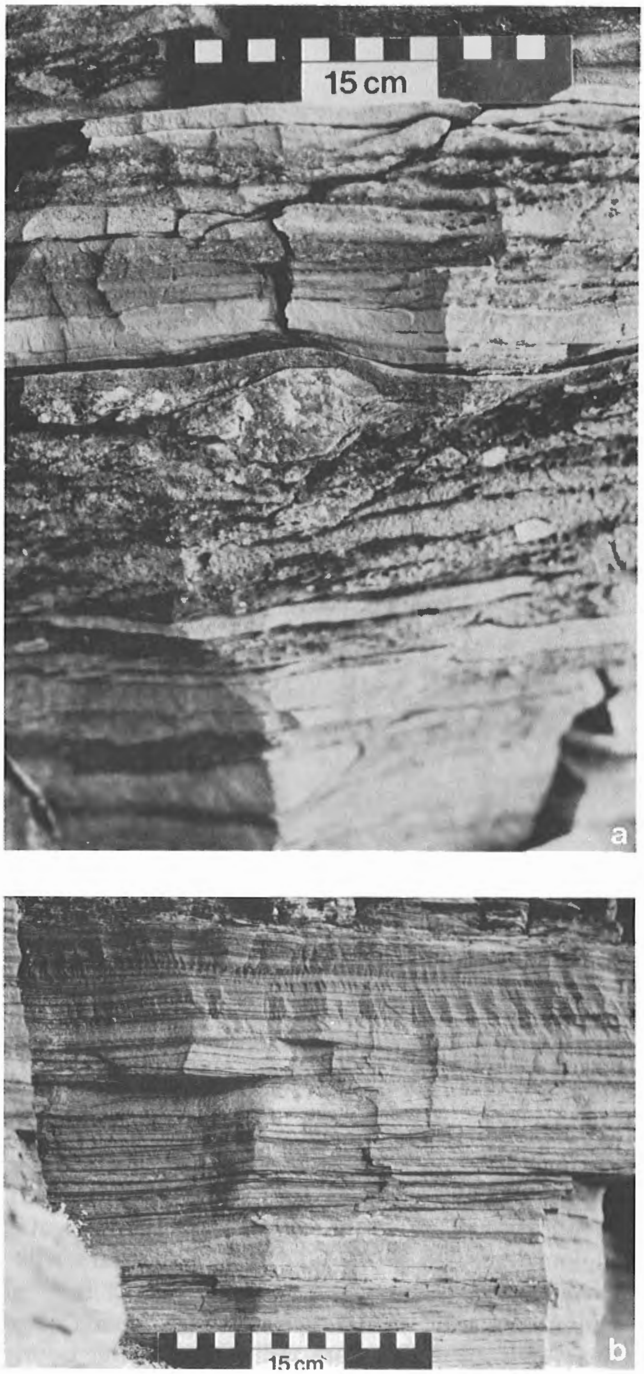


***Figure 26.*** *$C_1$ Unit laminated and crosslaminated, thin bedded sandstone. Note the bed of sedimentary-clast conglomerate in **a**.*

*Figure 27. $C_1$ Unit thin- to medium-bedded grey slate and chloritic slate. I.S.P.G. photo. 3819-1.*

*Figure 28. $C_1$ Unit outcrop near the upper part of the Khishchnikov River showing interbedded white gypsum, light brown and light grey weathering slate, siltstone and fine-grained sandstone. The gypsum is boudinaged. I.S.P.G. photo. 2672-17.*

*Figure 29. View looking west from the upper part of the Khishchnikov River showing Lower Carboniferous clastic rocks with gypsum (light coloured strata in the valley). Flatirons on the right are Carboniferous clastic rocks and the ridge on the left is underlain by Carboniferous strata. I.S.P.G. photo. 2672-11.*

In the western part of the island, in the area of the Gusinaya River drainage basin, the $C_1$ Unit is found as felsenmeer and scattered outcrops. Here the unit consists of a few hundred metres of variegated conglomerate with arkose and lenses of sugary white quartz sandstone, units of green slate, and beds of gypsum. Conglomerate clast sizes range from fine to coarse, and most clasts are well rounded, but poorly sorted. The most abundant clasts are white and red quartzite and green and greenish grey slate.

There are substantial differences among $C_1$ Unit strata across the island. The thickest and coarsest conglomerate appears to occur in the central island area. Conglomerate units also show rapid changes in character and thickness. Carbonate and gypsum units from the upper part of the $C_1$ Unit appear to be restricted to the central island.

***Age.*** The $C_1$ Unit has yielded fossils of Tournaisian and Viséan age. In the headwaters area of the Khishchnikov River, a collection of brachiopods suggests an Early Carboniferous age, no older than late Tournaisian (Appendix 1, $C_1$-F1). On the north slopes of the Mineeva Mountains Tournaisian conodonts have been recovered from this unit (Appendix 1, $C_1$-F5). Various beds in the succession produced spores common to the Carboniferous (see Appendix 1, $C_1$-F2; M.V. Oshurkova, pers. comm., 1989). In addition, in the upper gypsum-bearing part of the $C_1$ Unit, the remains of Early Carboniferous Viséan corals were

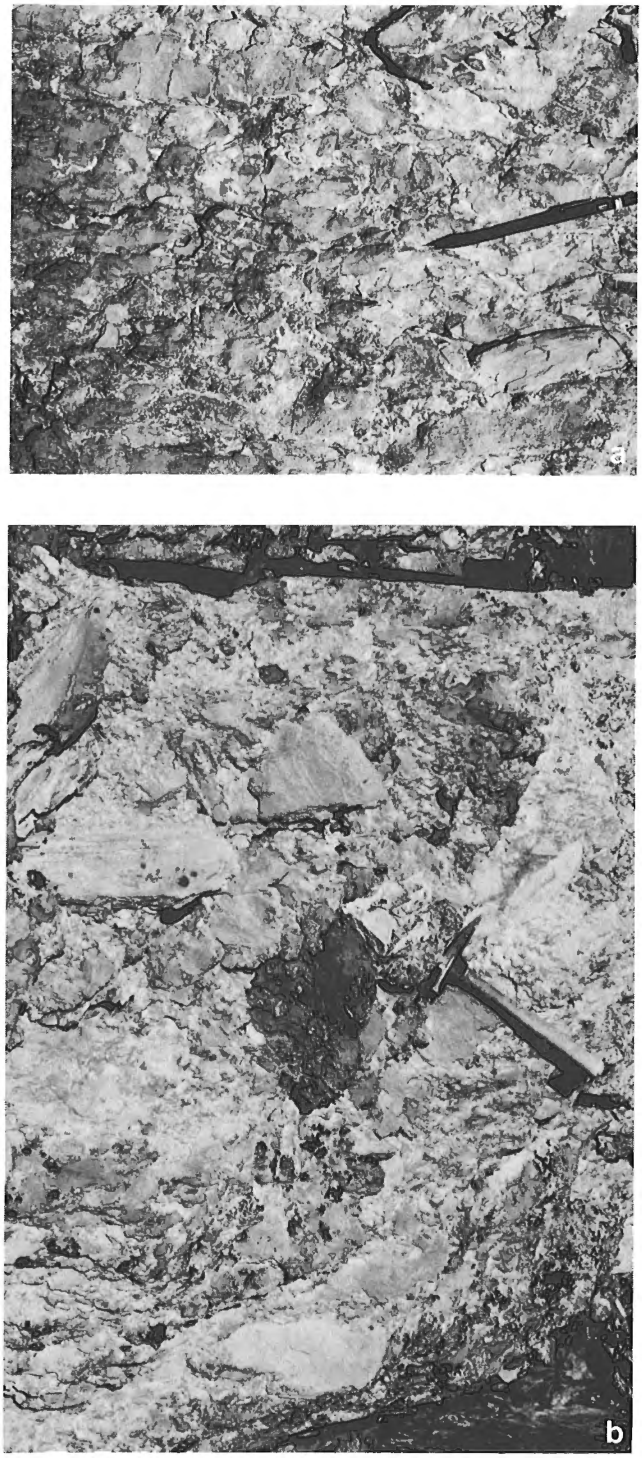

*Figure 30. Sedimentary-clast conglomerate. Pebbles are locally derived and consist of angular slate and sandstone pebbles and minor pebbles of vein quartz and pinkish red carbonate. Samples were photographed in the Tsentral'nye Mountains at the headwaters of the Somnitel'naya River. I.S.P.G. photos. 3819-6, 3819-8.*

identified from the headwaters of the Khishchnikov River (Appendix 1, $C_1$-F3). Because the underlying $D_{1-3}$ unit has yielded Upper Devonian (Frasnian) palynomorphs, the age range of the $C_1$ Unit may be restricted to the Early Carboniferous.

***Depositional environment.*** $C_1$ Unit strata represent a variety of lithofacies: sedimentary-clast conglomerate, fine and coarse grained clastic rocks, carbonate and gypsum (Fig. 31). In the central island area, upper Khishchnikov River, there is an upward transition from coarse clastic rocks, including sedimentary-clast conglomerate at the base to a facies complex represented by dolomite, limestone, slate, argillite and gypsum. To the south, on the north slopes of the Mineeva Mountains, the gypsum is missing and conglomerate clast sizes decrease. In the west, gypsum is found with sedimentary-clast conglomerate. In the north and northeast, in the upper Neizvestnaya and Krasnyi Flag river areas, neither carbonate nor gypsum have been observed, and coarse sedimentary-clast conglomerate is abundant. Also in the north, undated acidic and basic volcanic rocks are believed to be correlative with this unit (see following section).

The distribution of facies suggests an upland to the north, marginal mixed nonmarine and marine lagoonal facies down the centre of the island and basin facies to the south. The great variation in thickness of sedimentary-clast conglomerate and its immature and angular character suggest multiple local sources and a rift type of setting.

## Carboniferous(?) volcanic rocks

Volcanic rocks have been identified within inliers across the north-central part of the island. The exposures are found in the axial areas of map-scale anticlines in the drainage basin of the Krasnyi Flag and Neizvestnaya rivers. Previous reports have assigned these rocks to either the Proterozoic and Lower Cambrian succession (Kameneva, 1975) or to the middle Carboniferous "Kiberaskaya Suite" (Ageev, 1979). A possible Carboniferous age is inferred from indirect field evidence presented below.

At locality 14 near the upper Neizvestnaya River (Fig. 32), acidic volcanic rocks underlie Middle Carboniferous dolomitized limestone assigned to the $C_{1-2}$ unit. In one area, a discontinuous exposure of conglomerate separates the carbonate and volcanic rocks. Both the volcanic rocks and carbonate are in fault contact with Devonian slate and sandstone to the southeast. The volcanic rocks possess a primary, finely laminated texture, presumably the result of defor-

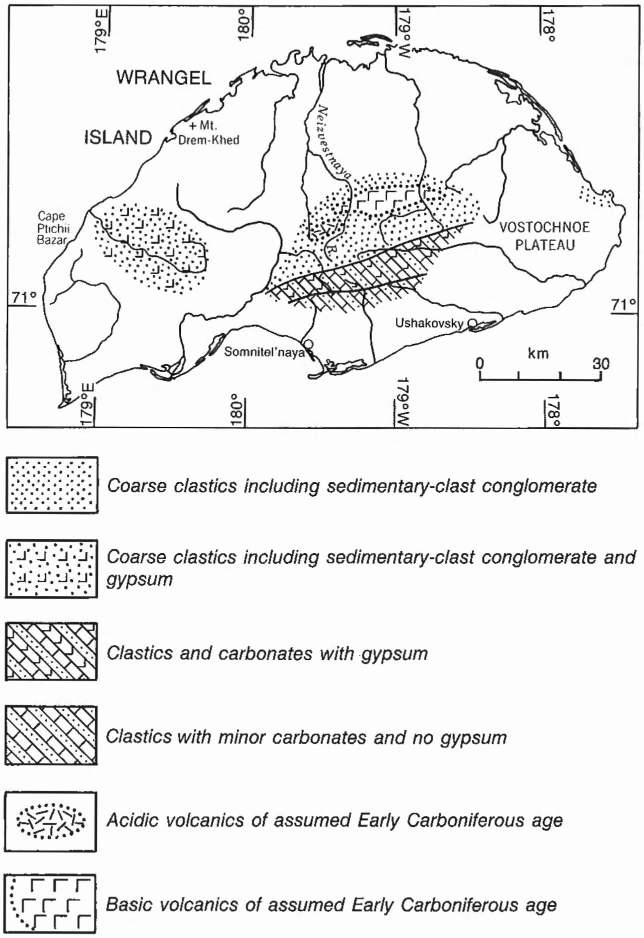


***Figure 31.*** *Paleogeography of the* $C_1$ *Unit.*

mation induced by gravitational compaction of fiamme and other explosive acidic volcanic materials during extrusive cooling.

At locality 15, farther north in the Neizvestnaya River area (Fig. 32), Carboniferous carbonate, outcropping above volcanic rocks, also overlies discontinuous basal conglomerate. The carbonate is faulted against Devonian slate to the southeast. The volcanic rocks are dark green, microcrystalline, and basaltic in composition with some primary amygdaloidal textures.

There are no known volcanic outcrops in the Krasnyi Flag River area. However felsenmeer, modestly shifted outcrops of conglomerate, and sandstone have been observed together with mafic igneous rocks, all stratigraphically below Carboniferous limestone. Frost-heaved exposures of igneous rocks are limited in one case to an area of only about 1.5 m by 0.5 m. However, geological relations indicate that the igneous body has intruded the conglomerate. The clast compositions in surrounding conglomerate include slate and vein quartz. Paradoxically, no igneous clasts have been noted and it can be assumed that volcanic flows and plutonic bodies of any sort were a rare or nonexistent component of the Carboniferous catchment area.

Although these volcanic exposures could conceivably be inliers of Wrangel Complex, a geologically complicated explanation would be required. For example, the Devonian clastic rocks illustrated on Figure 32 would have to have been eroded in pre-Carboniferous time across Devono–Carboniferous faults reactivated in post-Carboniferous time. The mid-Paleozoic faulting would have to have exposed Wrangel Complex rocks to Carboniferous erosion on the upthrown block, without leaving clasts typical of the Wrangel Complex in basal Carboniferous conglomerate.

Geological relations favour the proposal that a phase of volcanism and related plutonic activity possibly overlapped deposition of the Carboniferous ($C_1$ Unit) conglomerate in the northern part of the island. Indirect evidence places the volcanic rocks stratigraphically between middle Carboniferous carbonate above, and Devonian ($D_{1-3}$ Unit) slate and sandstone below. Nevertheless, there is no exposure in which volcanic rocks have been observed to lie unequivocally on Devonian clastic rocks.

## Lower to Upper Carboniferous ($C_{1-2}$ Unit)

***Definition.*** In the Tsentral'nye Mountains area, the $C_{1-2}$ Unit is well exposed and can be divided into two parts (Fig. 33). The lower part consists essentially of about 600 m* of microcrystalline and crinoidal biocalcarenite, fine grained, thin-bedded limestone, and minor slate and argillite. The upper part is an approximately 800 m* thick succession of limestone interstratified with slate and argillite. The limestone is dominantly crinoidal calcarenite. The $C_{1-2}$ Unit correlates approximately with the Uering Suite and upper member of the Yunona Suite of Ivanov (1973), and the Gusinaya Reka Suite, Kibera Suite and unnamed Lower Carboniferous limestone of Ageev (1979), all defined during earlier reconnaissance stratigraphic studies of the island (Fig. 4). Kameneva (1975), Kameneva and Chernyak (1975) and Chernyak and Kameneva (1976) recognized the widespread presence of Carboniferous strata on the island from which they identified Early and middle Carboniferous

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*Based on structural analysis (Fig. 51) the thickness here is considered to exceed the space available by a factor of two. See discussion in Appendix 1, Section $C_{1-2}$-1.

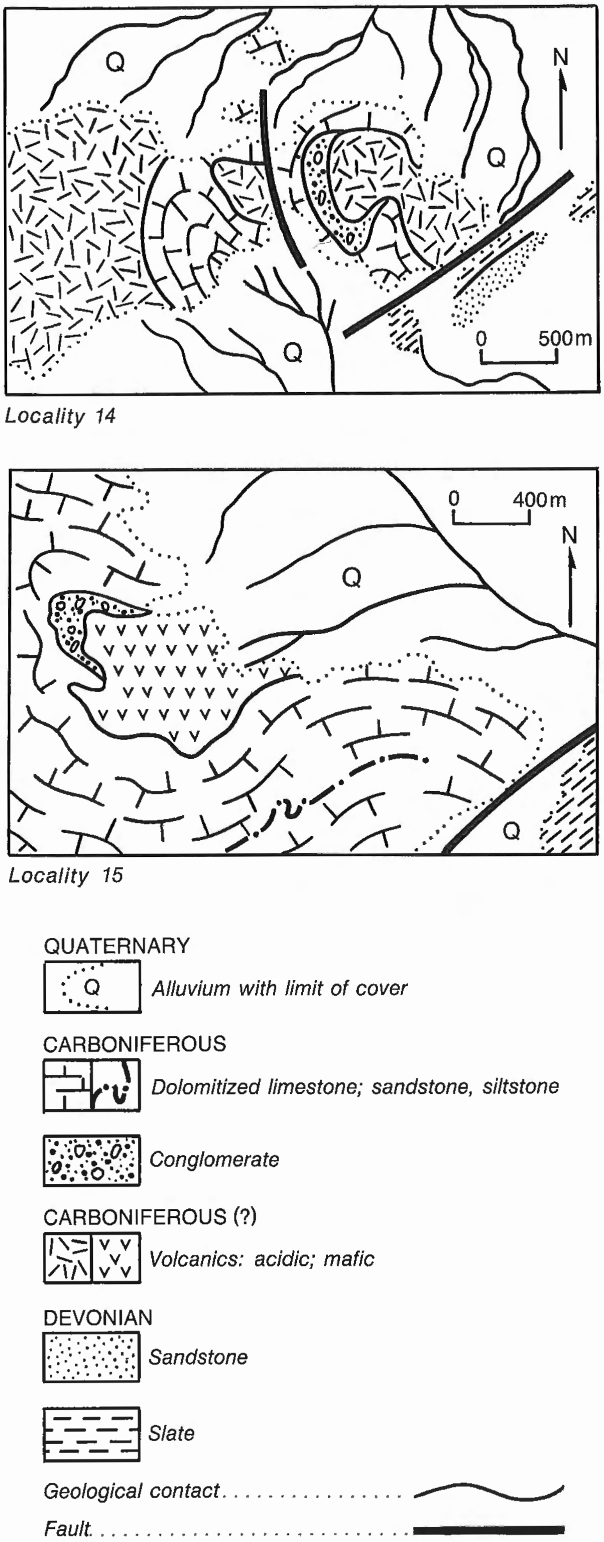


***Figure 32.*** *Sketches of the geology around volcanic occurrences in the headwaters area of the Neizvestnaya River. See Figure 2 for locations 14 and 15.*

fauna. Ganelin et al. (1989) locally subdivided the Carboniferous into three suites which were named, in ascending order, Cherningskaya, Khishchnikov and Chernyaskaya. These units will be the subject of a further report by him.

***Type locality.*** The type locality is a composite section measured in the headwaters area of the upper Khishchnikov River (Fig. 33)

***Distribution.*** The $C_{1-2}$ Unit can be traced almost continuously through the central island area from Cape Uering, in the east, to Cape Ptichii Bazar, on the west coast (Fig. 9). To the south it disappears into the subsurface below a vast exposure of Triassic strata, and in the north, beneath Cenozoic deposits of the coastal plain. Throughout its area of exposure it is found on the limbs of most major anticlinoria, in the Gusinaya River area, in the Mamontovye and Tsentral'nye mountains, as well as in the northern parts of the Vostochnoe (Eastern) Plateau.

***Contacts.*** The lower contact of the $C_{1-2}$ Unit is defined as the base of the first thick carbonate unit in the lower, limestone-dominated half of the succession (Fig. 34). In many places this limestone is conglomeratic and has beds of conglomerate. Across the island the contact with the underlying $C_1$ Unit and Carboniferous(?) volcanic unit is conformable in the south, and disconformable or unconformable over the rest of the island. The basal limestone unit is diachronous, varying in age from Early to middle Carboniferous.

In the headwaters area of the Khishchnikov River, the $C_1$ and $C_{1-2}$ contact is distinct, and apparently conformable. It is placed at the base of the first thick succession of grey limestone above a varied succession of $C_1$ clastic rocks with lesser dolomite and gypsum.

In the west-northwest, 10 km from the mouth of the Gusinaya River (Fig. 2, Loc. 13) , the lower contact can be traced continuously for 1.5 km. Here the limestone succession that forms the base of the $C_{1-2}$ Unit sits above felsenmeer of $C_1$ Unit conglomerate. The conglomerate includes thin, discontinuous beds of bright green slate. At this locality, the basal $C_{1-2}$ Unit limestone succession is 40 to 50 m thick, black to dark grey, thin bedded, and microcrystalline, and contains abundant Early Carboniferous fossils (Appendix 1, $C_{1-2}$-F1). The unit is overlain by as much as 40 m of a more massive, thick bedded, grey, fine to coarse grained limestone.

An unconformable sub-$C_{1-2}$ Unit contact with Carboniferous(?) volcanic rocks was also studied in the

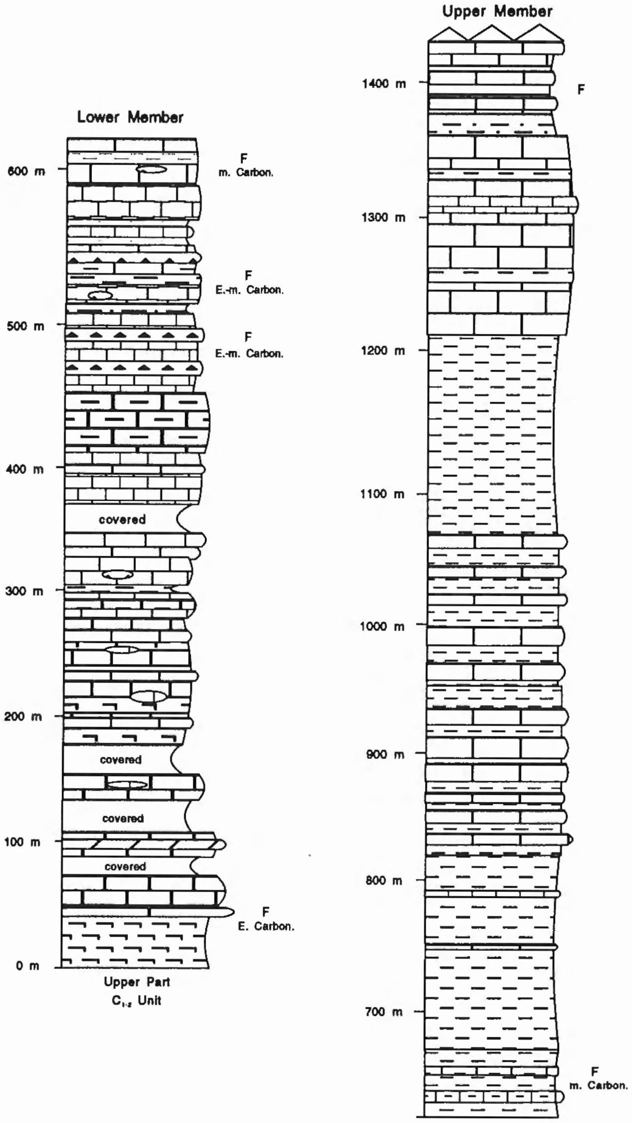


***Figure 33.*** *Composite stratigraphic section $C_{1-2}$-1, headwaters of the Khishchnikov River. For legend, see Appendix 2.*

***Figure 34.*** *View to the southwest of side of ridge. Lower $C_{1-2}$ carbonate strata on ridge overlie recessive $C_1$ Unit strata in valley. I.S.P.G. photo. 2672-33.*

north-central part of the island at three localities. The first is on the west bank of the upper Neizvestnaya River (Loc. 14, Fig. 32). $C_{1-2}$ limestone, outcropping near exposures of acidic volcanic rocks, contains both scattered volcanic clasts and conglomerate beds with abundant clasts of the volcanic rocks. At the second locality (Loc. 15, Fig. 32), basalt is exposed in the floor of a small amphitheatre and $C_{1-2}$ Unit limestone outcrops on the slopes of the amphitheatre. Along the contact between the two is a calcareous breccia-conglomerate with granule, pebble and boulder sized clasts. The composition and character of the conglomerate varies along strike. In one place it is red and consists of quartz, quartzite, quartz sandstone, and red, green and dark green siliceous volcanic rocks. Farther along the contact, the conglomerate is found in talus along with carbonate breccia. The breccia is composed of limestone and dolomite clasts with a red argillaceous carbonate cement. At a third locality (Loc. 16, Fig. 2) the contact zone can be described as follows. At the base are 3 to 4 m of breccia composed of very angular green basalt clasts with minor vein quartz and quartzite clasts, in a mafic volcaniclastic sandstone matrix. The breccia is gradational upward into a 2 m succession of coarse-pebble conglomerate with rounded basalt, quartz and quartzite clasts in a green mafic volcaniclastic sandstone matrix. This unit is overlain by 2 m of quartz granule sandstone and fine pebble conglomerate that upward becomes calcareous and is gradational into basal $C_{1-2}$ Unit limestone. The limestone here yielded Middle Carboniferous foraminifers (Appendix 1, $C_{1-2}$-F8). This information illustrates that the $C_{1-2}$ Unit unconformably rests on the Carboniferous(?) volcanic strata over a large part of the north-central area.

In the northeast the lower contact was mapped for over 8 km along strike in an overturned monocline (Loc. 11, Fig. 2, headwaters of the Naskhok River). The lower contact is exposed in a ridge of overturned south-dipping flatirons (Fig. 35). The structurally highest unit exposed is a succession of quartzite and slate (undivided $DC_1$ map unit), outcropping on the south face of the flatirons. Structurally below this is $C_{1-2}$ limestone, and below the limestone are $P_{1-2}$ Unit slate and sandstone, forming the low ground to the north. In the western part of the exposure, the $C_{1-2}$ Unit consists of massive dolomitic limestone with clasts of poorly rounded white and translucent quartz and slate in the stratigraphically lowest strata. The number of clasts increases to about 50 per cent of the rock to the east along the stratigraphically lower contact zone. In this zone talus blocks consist of limestone and diverse coarse clastic rocks. The clastic rocks include: well-rounded boulder conglomerate with carbonate-cemented quartz pebble and sand matrix; variegated and red conglomerate with pebbles and boulders of white quartz; slate with a slate matrix; very calcareous gritstone with crinoids; limestone with scattered slate pebbles; and fine-pebble conglomerate with slate clasts and a siliceous, calcareous cement.

***Composition.*** One complete composite, and one incomplete section have been measured through the $C_{1-2}$ Unit (Fig. 33). The $C_{1-2}$ Unit here is divisible into a lower, cryptocrystalline limestone and crinoidal limestone member (Fig. 36), and an upper member of interbedded crinoidal limestone and black slate with major units of black slate. This stratigraphy is typical of most of the central southern half of the island.

In the west, the upper $C_{1-2}$ Unit is represented by a major limestone bioherm exposed in the cliffs of Cape Ptichii Bazar (Fig. 37). The exposed part of the limestone bioherm is at least 80 to 100 m thick, and is composed of a complexly cemented algal framestone with rare brachiopods, goniatites and corals. Parts of the correlative flank succession around the bioherm are repeated along the coast by folding. The flank strata consist of coarse, thick and wavy-bedded crinoidal biocalcarenite. Within them, 3 to 4 cm long algal thalli in bedding orientation have been observed which, in places, form an intricately interwoven mosaic encrusted with carbonate cement. In the same beds, crinoid columnals are ubiquitous, brachiopods abundant, tetracorals rare, and goniatites very rare.

At the base of a hanging-wall thrust succession just north of the Mineeva Mountains, Khishchnikov River area, is a thin succession of brecciated and silicified

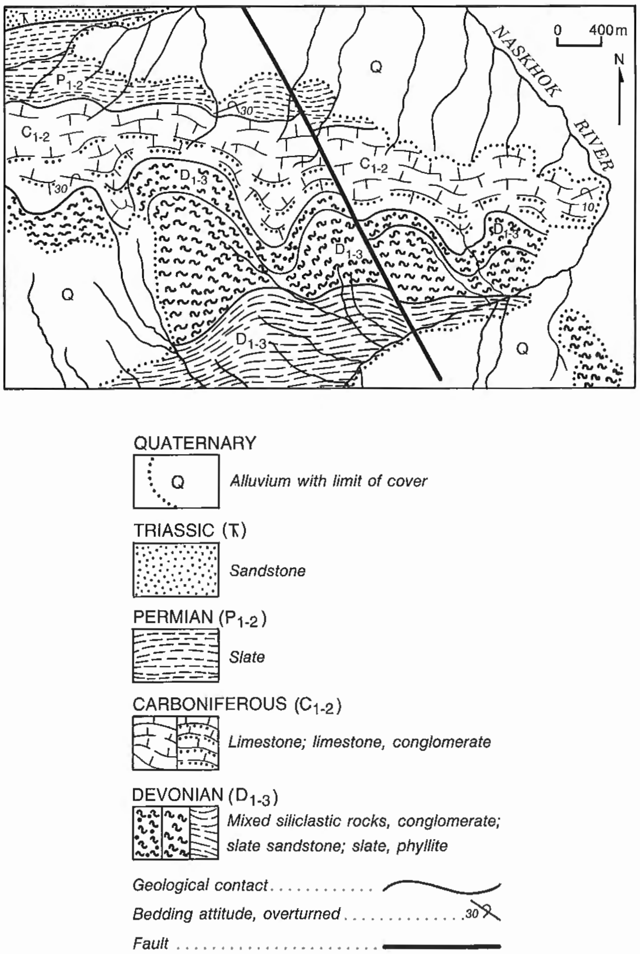


***Figure 35.*** *Detailed geological sketch map of overturned Devonian, Carboniferous and Permian strata. Locality 11, Figure 2, Vostochnoe Plateau.*

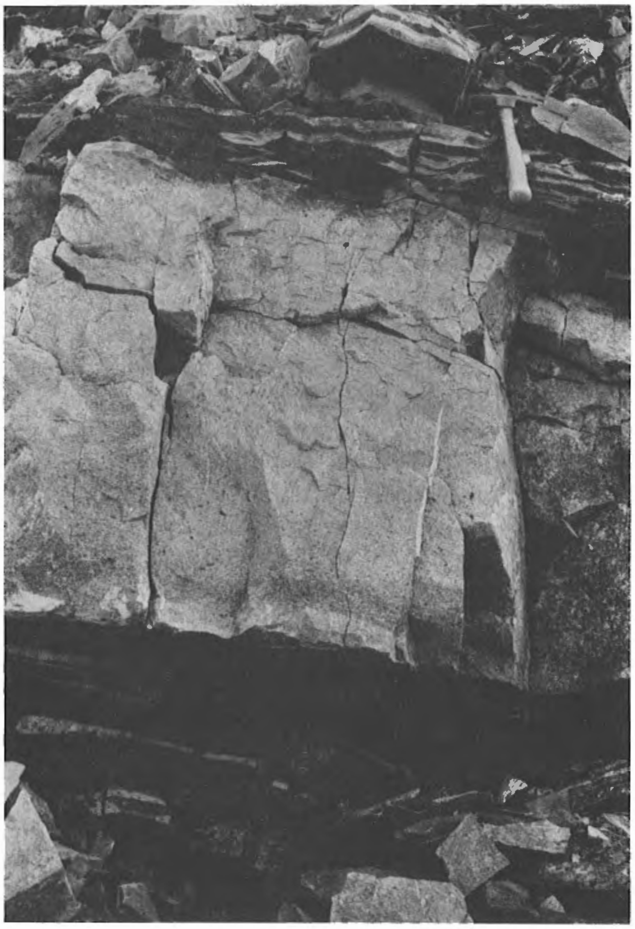

***Figure 36.*** *$C_{1-2}$ Unit interbedded crinoidal packstone (thick bed), and thin bedded argillaceous limestone and calcareous slate from the middle part of the Carboniferous unit. This outcrop is on the southern flanks of the Central Anticlinorium. I.S.P.G. photo. 2672-3.*

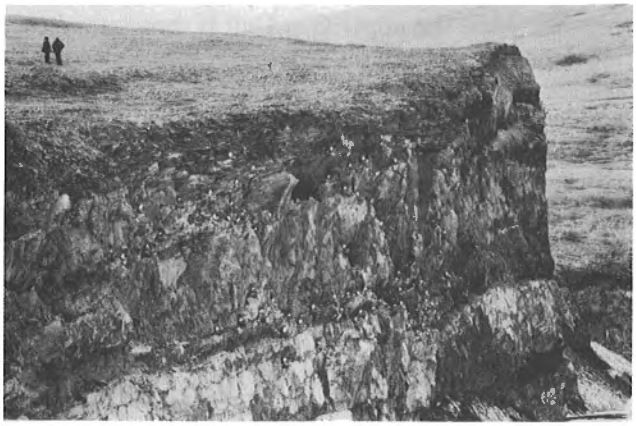

*Figure 37. Cape Ptichii Bazar. This prominent sea cliff is an important bird rookery on the west end of the island. It is composed of massive bedded $C_{1-2}$ Unit, with massive, pisolitic, algal(?), stromatolitic and multiple-cement textures. Note sea birds nesting. I.S.P.G. photo. 2672-25.*

dolostone, which structurally underlies the $C_1$ Unit, but which, according to cleavage and bedding intersections, stratigraphically overlies the $C_1$ Unit. These strata are believed to be altered $C_{1-2}$ carbonate.

In the east, the $C_{1-2}$ Unit is estimated to be 400 to 500 m thick and forms 200 m high cliffs at Cape Uering. In the Cape Uering area the lower part of the $C_{1-2}$ Unit strata are extensively dolomitized, and some of the succession is interpreted as a dolomitized bioherm. Generally the dolomite is massive, well indurated, light grey to white, in places greenish, yellowish, pinkish and dusky red. The rocks are silicified, and shot through with quartz. Locally the carbonate is completely replaced by silica. In spite of this, relics of fossils and poorly preserved fossils with encrusting cements are relatively common. Algal thalli, hydrozoa, corals, crinoids and brachiopods have been observed (Appendix 1, $C_{1-2}$-F17). High in this cliff succession some lamination is highlighted by silica replacement, and the carbonate consists of limestone and dolomite.

The upper part of the $C_{1-2}$ Unit is exposed in the southern part of Cape Uering and is composed of fine to medium grained, locally crinoidal, sandy limestone, with thin beds of black slate. The proportion of slate increases upsection and the strata are gradational with the overlying $P_{1-2}$ Unit.

In the north-central part of the island, in the drainage areas of the Neizvestnaya and Krasnyi Flag rivers, the $C_{1-2}$ succession is 300 to 400 m thick and consists of bryozoan and algal biohermal limestone, coarse calcarenite, and crinoidal calcisiltite, with interbeds of sandstone, siltstone and conglomerate. The limestone contains rare pebble and coarse sand grains as well as minor dolomite.

In the northeast, the $C_{1-2}$ Unit was observed in the headwaters of the Naskhok River. The succession is overturned and dips southward, structurally under the $DC_1$ Unit and above the $P_{1-2}$ Unit. The stratigraphic lower part is conglomeratic (see contacts). The succession is dominantly limestone and includes algal-crinoidal wackestone with lump-shaped plates and floating ossicles in microcrystalline limestone; crinoidal calcarenite; microcrystalline dolomitic limestone; and thin bedded lenticular algal limestone with very thin black slate interbeds. The carbonate contains corals, bryozoans and foraminifers (Appendix 1, $C_{1-2}$-F18).

***Age.*** The $C_{1-2}$ Unit is dated as Early to middle Carboniferous (Appendix 1). Basal limestone units have yielded corals, brachiopods, bryozoans, crinoid ossicles and rare gastropods ($C_{1-2}$-F1). The brachiopods give a Late Tournaisian to Viséan age. Conodonts from about 20 m below the top of a bioherm at Cape Ptichii Bazar suggest an early to middle Moscovian age (Appendix 1, $C_{1-2}$-F4). Brachiopods and goniatites collected from the top of the same bioherm indicate a middle Bashkirian or Early Moscovian age (Appendix 1, $C_{1-2}$-F3, F4). The uppermost age limit of the $C_{1-2}$ Unit in the north is Moscovian (Appendix 1, $C_{1-2}$-F7) or younger, and could range as young as Early Permian.

In the type area, near the headwaters of the Khishchnikov River, Chernyak and Kameneva (1976) reported fossils typical of the late Tournaisian at the base of the succession, and Viséan fauna stratigraphically a little higher at the same locality. In the same area fauna were recovered from the middle part of the $C_{1-2}$ Unit and ammonoids in this collection are interpreted as middle Bashkirian by M.F. Bogoslovskaya (see Appendix 1, $C_{1-2}$-F13).

In the areas of the upper Nasha and Khishchnikov rivers, Chernyak and Kameneva (1976) and G.I. Kameneva (pers. comm., 1988) reported collecting Namurian fauna from the $C_{1-2}$ Unit (Appendix 1, $C_{1-2}$-F6). From different sites in the drainage areas of the Neizvestnaya and Krasnyi Flag rivers, abundant foraminifers, bryozoans, brachiopods, crinoids and rugose corals generally considered to be Moscovian (Appendix 1, $C_{1-2}$-F7), were collected.

*Depositional environment.* Two normal-marine facies belts can be recognized in the $C_{1-2}$ Unit, a shallow-water carbonate-dominated facies with bioherms in the north and west, and a limestone–slate transitional to basinal facies belt in the south-centre and southeast. In addition, there is an upward transition from shallow-water facies to transitional facies (Fig. 38).

Fossil assemblages and lithologies indicate a normal low-latitude marine setting. Platform carbonates comprise cryptocrystalline carbonate, clastic carbonate with crinoidal grainstone, and algal–bryozoan bioherms. Except for the algal–bryozoan bioherms, the same lithologies are found interstratified with basin facies slate in the transitional zone, in the south-centre of the island (Figs. 33, 38).

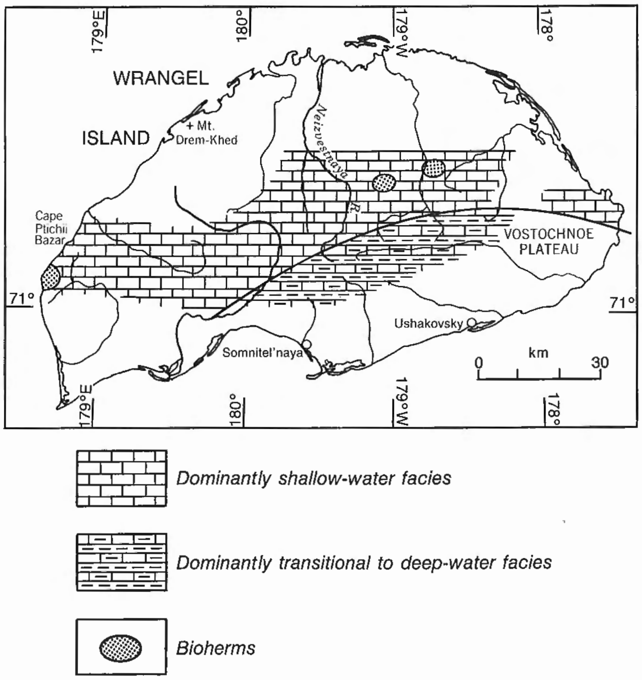


*Figure 38. Paleogeography of the $C_{1-2}$ Unit.*

## Lower to Upper Permian ($P_{1-2}$ Unit)

*Definition.* Over much of the island, Permian strata ($P_{1-2}$ Unit) consist of up to 750 m of slate and limestone with minor sandstone, coarse clastic rocks and siliceous strata. In the north however, the lower part contains an olistostrome-breccia complex overlain by limestone, which is in turn overlain by a thick succession of slate and limestone. In earlier mapping, this unit was generally lumped with older units, unless its' age could be substantiated with paleontological control (Kameneva and Chernyak, 1973, 1974, 1975; Fig. 4). $P_{1-2}$ Unit strata, however, are a distinct mappable unit that can be further subdivided with detailed mapping (Fig. 9).

*Type locality and reference areas.* The type section of the $P_{1-2}$ Unit is situated in the Khishchnikov River area 39; Locs. 20, 21, Fig. 2). A reference area is situated between the Neizvestnaya and Tundrovaya rivers, in the northern part of the island.

*Distribution.* In the south the $P_{1-2}$ Unit is exposed throughout the mountains with very few breaks from Cape Ptichii Bazar in the west to Cape Pillar in the east. In the northwest, these strata underlie a large area of Triassic strata in the Bezymyannye Mountains. $P_{1-2}$ Unit strata are ubiquitous in the central and northeastern parts of the island, where they are poorly exposed, but can be mapped, with difficulty, along the limbs and in the cores of folds.

*Contacts.* Kameneva and Chernyak (1973, 1974, 1975) considered Permian strata to be separated from Lower and middle Carboniferous strata by a hiatus that spanned the Late Carboniferous and Early Permian. However, the boundary over much of the island area, with exceptions, appears conformable and is placed at the point where the $C_{1-2}$ Unit succession of carbonate, slate and argillite grades upward into a dominantly slate and argillite succession ($P_{1-2}$ Unit).

In the southern part of the island, the $P_{1-2}$ Unit rests conformably on $C_{1-2}$ Unit strata with no apparent break. The contact between the two units is placed at the stratigraphic level where carbonate rocks are replaced by slate. In the headwaters area of the Khishchnikov River, the boundary is gradational and is drawn between a succession of interstratified limestone and slate, below, and a 250 m thick succession of monotonous slate, above.

In the Ptichii Bazar area the contact is distinct, sharp and probably disconformable. At this locality, $C_{1-2}$ Unit biohermal limestone is directly overlain by a $P_{1-2}$ Unit sandstone with local sedimentary breccia and pebble conglomerate.

Over much of the northern area, the contact is placed above $C_{1-2}$ carbonate and below a basal $P_{1-2}$ Unit sandstone, which can be traced mainly in felsenmeer, but is present in outcrop on the west bank of the Neizvestnaya River, about 15 km upstream from the mouth of the Lemmingovaya River (Fig. 2). Farther north there is a significant unconformity below the $P_{1-2}$ Unit. Detailed mapping of poorly exposed strata at the junction of the Lemmingovaya and Neizvestnaya rivers (Loc. 19, Figs. 2, 9) shows an overturned fold with fossiliferous Silurian strata in the core (Appendix 1, $S_2D_1$–F4), disconformably overlain by Permian breccia (Fig. 40).

***Composition.*** In the south-central area the $P_{1-2}$ Unit is greater than 790 m thick and is dominated by slate. It is divided into three members (Fig. 39): a lower unit of black-green and off-white argillite (Fig. 41); a middle varicoloured argillite with limestone ("variegated") unit; and an upper member of black slate with sandstone lenses (Fig. 42). Northward, in the Neizvestnaya River area, a composite section (Fig. 39) contains a basal unit of boulder and block breccia with conglomerate composed of slate, quartzite, quartz, basalt, conglomerate and limestone clasts, overlain by a unit of limestone, which in turn is overlain by a unit of slate with sandstone. This composite northern section is about 1000 m thick. At Cape Ptichii Bazar, the $P_{1-2}$ Unit, exposed along the coast, is divisible into a lower succession of green slate with sandstone, a middle "variegated" unit of limestone and clastic strata (Figs. 43–45) and an upper unit of green and black slate. In a section measured near the coast, north of Ptichii Bazar, the middle "variegated" unit is relatively thick and contains silicified limestone and fine pyrite nodules (Appendix 2, $P_{1-2}$ Section 2). In the Cape Uering area, the $P_{1-2}$ Unit is predominantly slate with sandstone and the middle limestone or "variegated" unit is missing.

Rock-Eval analysis of a foetid Permian limestone gave essentially no hydrocarbon generation potential and a very low TOC value of 0.07 per cent. These data indicate this rock has matured well beyond the oil generation window (L.R. Snowdon, pers. comm., 1987).

***Age.*** Both Early and Late Permian macrofossils have been collected from northern exposures of the $P_{1-2}$ Unit (Appendix 1). $P_{1-2}$ Unit limestone beds in the middle and upper parts of the Neizvestnaya River section and outcrops near the Khishchnikov River contain fragments of the bivalve *Kolymia,* which led Kameneva and Chernyak (1975) and Chernyak and Kameneva (1976) to conclude that these are likely analogs of the Dzhigdalin Suite, considered to be late Early Permian in age (Eliseeva et al., 1984). However, W.W. Nassichuk (pers. comm., 1991) feels that *Kolymia* may be either Early or Late Permian in age. Limestone blocks in the basal breccia in the Neizvestnaya River area yielded redeposited Silurian corals, and one brachiopod was collected from a block which ranges from Late Carboniferous to Permian in age (Appendix 1, $P_{1-2}$–F19).

In the southern part of the island, as noted in the section on the $C_{1-2}$ Unit, neither the upper age of the $C_{1-2}$ Unit or the lower age of the $P_{1-2}$ Unit is constrained. Thus the possibility remains that locally these undated strata represent a continuous Middle Carboniferous to Permian succession with the system boundary located within either the upper $C_{1-2}$ Unit or lower $P_{1-2}$ Unit. The upper black slate beds of the $P_{1-2}$ Unit, over most of the island, are apparently transitional into the Tr Unit. This part of the section is biostratigraphically uncontrolled and it is possible that some of the slate is Triassic in age.

***Depositional environment.*** $P_{1-2}$ Unit strata represent several different facies zones (Fig. 46). In earliest Permian the presence of a lower olistostrome-breccia complex juxtaposed on $S_2D_1$ strata indicates uplift and erosion on the north-central part of the island. The rest of the area comprises basin facies with abundant mudstone and argillaceous calcarenites containing coquina. In the latest Permian a terrigenous shallow-water platform was established in the northwest and was bordered to the southeast, in order of proximity, by a transitional (mixed platform and basin) facies belt, a basin facies belt with slate, pyrite and rhodochrosite nodules and finally by a belt of slate and chert. Stratigraphically, the highest Permian unit is a black slate–argillite succession, which may be transitional into the Triassic and which is interpreted as a starved basin facies associated with drowning of the entire island area.

## Triassic (Tr Unit)

***Definition.*** Tr Unit strata on Wrangel Island consist mainly of an approximately 800 to 1500 m thick, monotonous, repetitive succession of interstratified, black, turbiditic sandstone and slate. The first detailed stratigraphic and biostratigraphic data on the Tr Unit were presented in Til'man et al. (1970) and Ivanov (1973).

***Reference locality.*** Because of the internal compositional homogeneity of the Triassic succession and extensive internal deformation, no section was measured through it. However Ivanov (1973) presented measured stratigraphic data from the Cape Pillar area. In addition, the only fossils recovered from the Tr Unit were found in the Klark River–Cape Pillar area. Thus this area is considered to be a reference area for the Tr Unit.

***Distribution.*** Triassic strata on Wrangel Island are exposed in a south-dipping homocline 5 to 20 km wide and traceable from Cape Ptichii Bazar, on the west,

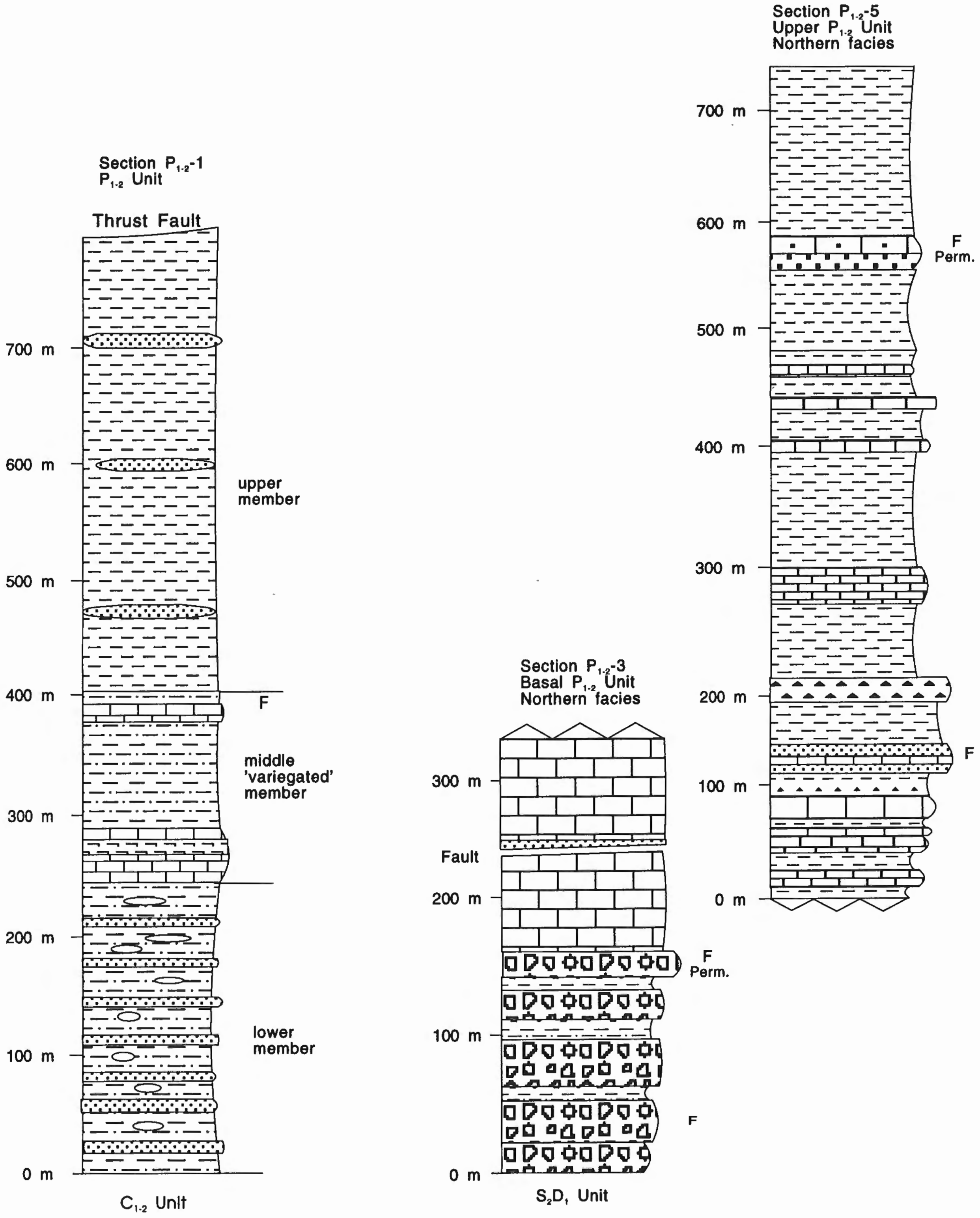


***Figure 39.*** *Type section of the $P_{1-2}$ Unit from the Khishchnikov River area and reference composite section from the Neizvestnaya River area. For legend, see Appendix 2.*

through the Yevstifeeva and Mineeva mountains, to beyond the Klark River, on the east. Triassic strata are also recognized in the Bezymyannye Mountains, in the area between the Tundrovaya and Neizvestnaya rivers, and in the headwaters area of the Naskhok River (Fig. 9).

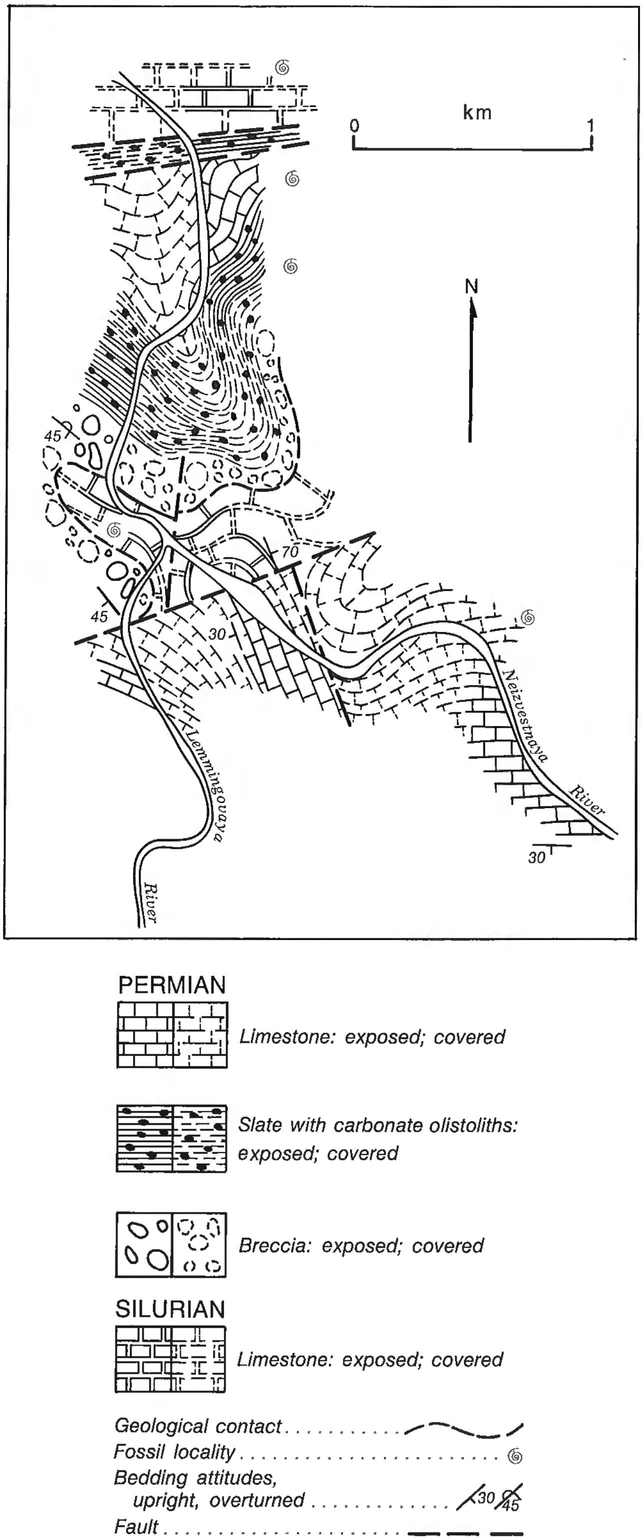


***Figure 40.*** *Detailed geological map of the area near the mouth of the Lemmingovaya River, illustrating the contact between Permian olistostrome-breccia and the $S_2D_1$ Unit.*

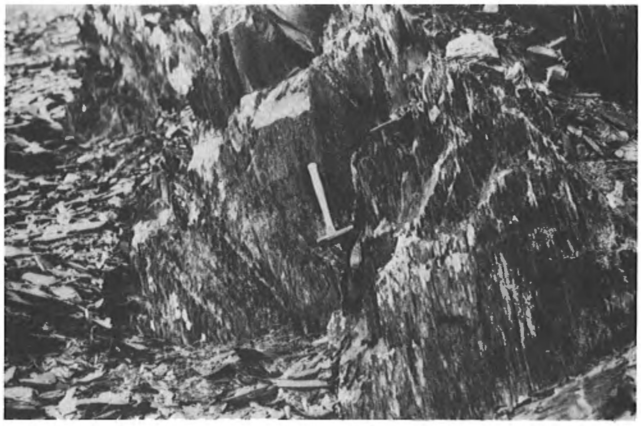

***Figure 41.*** *Dark green slaty argillite near the base of the $P_{1-2}$ Unit, Khishchnikov River area. I.S.P.G. photo. 2672-30.*

***Figure 42.*** *$P_{1-2}$ unit slate, black outcrop in middle ground overthrust by $C_{1-2}$ Unit dolostone. View looking south from the upper Khishchnikov River. I.S.P.G. photo. 2672-13.*

In the south, the most complete exposures are found south of Cape Ptichii Bazar, on the southwestern coast, and near the outlet of the Klark River in the east. In the Mineeva Mountains, exposures on the Khishchnikov River, its tributaries, and along several other rivers provide a series of sections through the Triassic consisting of felsenmeer, talus, and scattered outcrops.

***Contacts.*** Over most of the island the Tr Unit is apparently conformable with $P_{1-2}$ Unit strata. However, Ageev (1979) noted up to 2 m of basal conglomerate at scattered localities. Also Kameneva and Chernyak (1973) reported observing conglomerate at the base of the Triassic in the central part of the

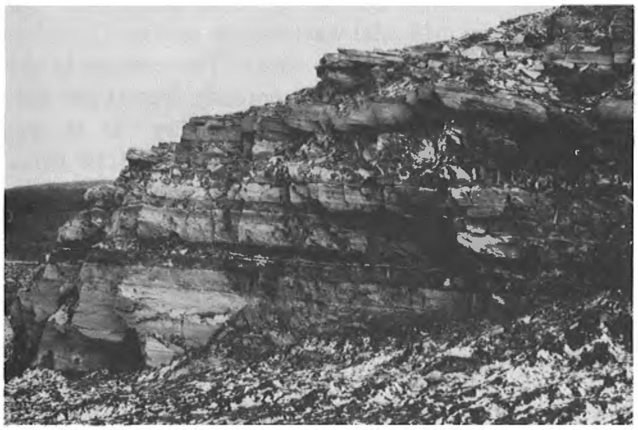

*Figure 43. Interbedded light green, slaty argillite, brown, foetid limestone, and grey slate of the middle (variegated) beds of the $P_{1-2}$ Unit, sea cliff exposures, north of Cape Ptichii Bazar. This argillite contains large idiomorphic pyrite cubes and some disseminated pyrite, which to the south is found in massive to crystalline nodules. In exposures south of Cape Ptichii Bazar this succession includes grey weathering, thick bedded crinoidal packstone. I.S.P.G. photo. 2672–27.*

*Figure 44. Load structures and soft sediment deformation in sandstone beds overlying green, slaty argillite in the middle of the $P_{1-2}$ Unit, Cape Ptichii Bazar area. I.S.P.G. photo. 2672–26.*

*Figure 45. Soft-sediment folds in $P_{1-2}$ sandstone, Cape Ptichii Bazar. I.S.P.G. photo. 3819–17.*

island. On the north slopes of the Mineeva Mountains the Tr Unit rests directly on $C_{1-2}$ and on $C_1$ Unit strata (Fig. 47).

The Triassic unit also appears to rest unconformably on $C_{1-2}$ Unit limestone in the headwaters area of the Somnitel'naya River. This contact is well exposed for several kilometres along strike and at least 3 km downdip. Everywhere in these exposures the Triassic unit rests on about the same thickness of Carboniferous limestone. Therefore any erosional or structural truncation surface, if present, must have dip values of less than 5°.

In basal Triassic unit exposures just east of the Khishchnikov River in the Mineeva Mountains, we observed truncation of a thin $C_{1-2}$ Unit limestone, from west to east, over a distance of about 4 km. This truncation also requires an angular relation of less than 5°. However, Til'man et al. (1970) examined the same area and reported that the contact between the Triassic unit and upper Paleozoic units is a 15 to 20° angular unconformity. We believe he was observing steep dips in small, locally detached contractional structures, which occur a few metres below the unconformity in this area.

We also observed the basal Triassic Unit contact near Cape Ptichii Bazar where it appears to conformably overlie the $P_{1-2}$ Unit. Here the contact is arbitrarily placed at the first thick sandstone succession overlying upper black slate of the $P_{1-2}$ Unit. In the Bezymyannye Mountains and several localities in the north, the Tr Unit rests directly on the $P_{1-2}$ Unit, although the actual contact is not exposed.

Near Cape Pillar, the basal strata have been described by Til'man et al. (1970) and Ivanov (1973) as consisting of 15 to 20 m of crosslaminated and ripple crosslaminated sandstone and very fine-pebble conglomerate containing clasts of quartz, black schist, and feldspar in sub-equal proportions. This description is different from any basal Triassic we observed and it

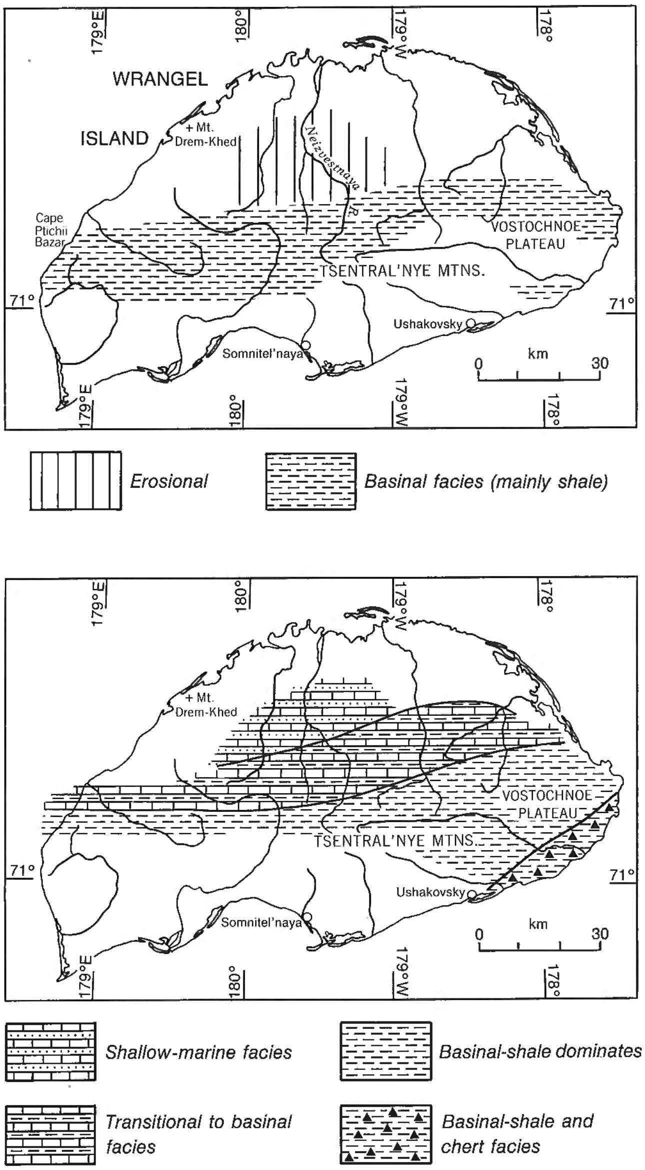


***Figure 46.*** *Paleogeographic maps of the lower and upper parts of the $P_{1-2}$ Unit.*

is possible that part of the Cape Pillar section includes either older strata or the difference is artificial. We assume the latter because Ivanov (1973) also stated that the Carboniferous and Upper Triassic succession south of Cape Ptichii Bazar, and along the Khishchnikov River, where we observed turbiditic sandstone and slate, is analogous to Carboniferous and Upper Triassic strata at Cape Pillar.

The contact between basal Triassic strata near the Khishchnikov River and at the headwaters of the Somnitel'naya River (Fig. 2) is problematic. In these localities, medium to thick beds of dark grey to black, fine grained turbiditic sandstone and some interbedded black slate directly rest on $C_1$ Unit sandstone with minor slate and crinoidal wackestone, and on $C_{1-2}$ Unit limestone and coarse clastic rocks. The contact in the immediate area is sharp and apparently free of any sort of basal conglomerate or pebble lag. It is not completely exposed but it can be traced in three dimensions as a sharp, south-dipping surface. The actual surface area is unassociated with structural complications, such as gouge, Riedel shears, quartz veins, high strain indicators, minor folds or faults. Minor folds were observed a few metres below the contact.

This contact is interpreted by MPC and MKK as a disconformity, however JCH hypothesizes that the juxtaposition of Triassic on these older units may be the result of later omission of strata by normal faulting (see Fig. 51, and Structural geology). NVK interprets this juxtaposition to be the result of structural omission associated with an-out-of-sequence low-angle reverse fault.

***Composition.*** Triassic strata preserved after post-Chukotkan erosion are estimated to be 800 to 1000 m thick by Til'man et al. (1970) and as much as 1500 m by Kameneva (1975). At 300 to 400 m structurally above the base of the Triassic south of Cape Ptichii Bazar, intraformationally detached tectonic folds are common. Maximum structural thickness, assuming a 10° dip over 20 km, is 3470 m. However this estimate includes tectonic thickening, and a true thickness may be about half this value. Metre-scale folds and thrusts are observed or inferred throughout the Triassic succession. With such a complex intraformational structure it is impossible to measure or estimate the

***Figure 47.*** *Tr Unit strata overlying $C_{1-2}$ Unit strata, north slopes of the Mineeva Mountains (Triassic dark unit on right and Carboniferous light unit on left; view to the southeast). I.S.P.G. photo. 2672-2.*

true thickness of the succession or the extent of internal thrust repetition. But because of the internal deformation we consider the values reported to be essentially structural thicknesses. Moreover, the top of the Triassic strata has been peneplained and covered with Quaternary alluvium.

In general, the Triassic on Wrangel Island consists of a succession of black sandstone and slate. South of Cape Ptichii Bazar, sandstone beds in the Tr Unit (Figs. 48, 49) display some of the classic elements of a very thick bedded turbidite assemblage, including normally graded bedding, sole marking, flutes, large-scale scours, load structures, and rip-up clasts (A to C divisions, Bouma cycle). Many sandstone beds are massive at their bases, and become laminated and convoluted upward. There is also a tendency to darken upward, indicating a decrease in grain size and/or an increase in argillaceous and organic content. The thickest sandstone beds are 1.5 m thick.

Samples examined from the Khishchnikov River area and Cape Ptichii Bazar consist of fine to medium grained sandstone composed predominantly of grains of quartz and fine grained sedimentary rock clasts, and 10 to 15 per cent plagioclase in a matrix of less than 10 per cent muscovite and low-birefringent mica minerals. All grains are tectonically altered so that now they essentially appear as an interlocking mosaic of clasts with millimetre-scale undulating foliation planes. In this state it is difficult to distinguish unequivocally between lithic clasts and matrix; however, the clotted nature of most concentrations of mixtures of fine grained minerals and quartz suggest lithic fragments were abundant in some samples.

Semiquantitative X-ray analysis shows a sample of Triassic sandstone from near the base of the Triassic unit section, Cape Ptichii Bazar as consisting of 37 per cent quartz, 29 per cent albite, 21 per cent chlorite, 8 per cent dolomite and 5 per cent muscovite. Thus the low-birefringent clots interpreted as grains of lithic material are likely a mixture of silica, chlorite and albite. Samples of Tr Unit slate from the middle part of the succession on the Khishchnikov River were determined by semiquantitative X-ray analysis to have 10 to 20 per cent quartz, 35 to 40 per cent chlorite, 20 to 25 per cent muscovite, 15 to 20 per cent albite and minor alkali feldspar.

The bulk of the Tr Unit sandstone from the southeast part of the island is reported to consist of fine grained arkosic sandstone, shale, and minor siltstone (Til'man et al., 1970, Ivanov, 1973). Sandstone in this part of the section consists of medium to coarse grains comprising equal amounts of

***Figure 48.*** *Triassic greywacke beds up to 1.5 m thick interbedded with recessive black slate, south of Cape Ptichii Bazar. The base of the thick beds is scored with tool marks, grooves, flute marks and load casts. Structures associated with the greywackes are normal grading, flat and convolute laminae, intraclasts, poor sorting and high matrix content. I.S.P.G. photo. 2672–28.*

plagioclase and quartz, minor chert, and a muscovitic matrix making up 35 per cent of the rock. Although the Triassic succession is sandstone dominated, individual units vary from sandstone with slate to slate alone, Til'man et al. (1970) and Ivanov (1973) also reported that near the outlet of a small tributary into the Klark River, friable conglomeratic sandstone interbedded with red argillite outcrops among Upper Triassic strata.

Rock-Eval analysis of a black Triassic slate indicated essentially no hydrocarbon generation potential and a very low TOC value of 0.28 per cent. These data indicate this rock has matured well beyond

*Figure 49. Flute casts on the underside of a thick Triassic sandstone bed south of Cape Ptichii Bazar. I.S.P.G. photo. 2672–29.*

the oil generation window (L.R. Snowdon, pers. comm., 1987).

***Age.*** The only Triassic fossils collected are from two sites found in relatively high structural positions near the outlet of the Klark River and in the area between the Klark River and Cape Ptichii Bazar (Appendix 1, Tr–F1, F2). The collections are pelecypods and are dated as Norian. Thus the actual age of the Tr Unit over most of the island is largely undetermined and there is a good possibility that older Triassic strata will be found.

The Tr Unit is the youngest pre-tectonic unit on Wrangel Island and its upper limits are the present-day or sub-Quaternary unconformities, although Tertiary deposits are known on the northern part of the island.

***Depositional environment.*** Tr Unit sandstone successions are typical proximal turbidites. The relatively thick turbidites (up to 1.5 m) indicate either a very proximal source or deposition near the outlet of a submarine channel. The finer grained clastic rock successions with which they are interstratified are either distal turbidites or off-axis lateral equivalents to proximal turbidites. The petrography of these sandstones alone is equivocal and indicates that the source area was dominantly pre-existing supracrustal strata and/or crystalline basement. However, given that the time equivalent Triassic on the adjacent northern Chukotkan Peninsula contains significant units of volcanic rocks (Yu.M. Bychkov, pers. comm., 1988), it is likely that these turbidites were derived from uplifts associated with volcanism on the south (see Tectonic history).

## Paleogene and Neogene

Paleogene and Neogene (Miocene) deposits, a few tens of metres thick, were observed in small outcrops in the lower parts of the Tundrovaya River (V.V. Avdyunichev, pers. comm., 1986 and O.N. Vinogradova, pers. comm., 1988). These rocks have a distinct geomorphology and examination of aerial photographs suggests the presence of similar strata in the lower parts of the Krasnyi Flag River. At a site 4 km east of the outlet of the Nasha River, orange to ochrous clay, with debris from the Tr Unit (siltstone and slate), are exposed in a 1.5 to 2 m high beach scarp. This clay is also thought to be Tertiary. The clay is 45 per cent kaolinite, 50 to 55 per cent hydromica and 0 to 5 per cent chlorite.

The Tundrovaya River exposures consist of grey, calcareous siltstone and well indurated, dark grey clay containing gravel and wood debris. Fragments of pelecypods and bryozoans are present, as well as foraminifers, algae, sponge spicules, abundant spores, pollen and diatoms (Appendix 1, PN–F1). The foraminifers indicate a Late Paleogene or even Neogene age. Spores and pollen indicate a moderately warm climate and an Oligocene–Miocene age (Avdyunichev and Volodin, 1989).

## Pliocene and Quaternary

A few metres of Pliocene deposits cover much of the northern part of the island, in the Tundra Akademii, and along a small strip on the southern coast (Fig. 9). On the north these coastal plain deposits are dominantly indurated Late Pliocene mud with pebbles and gravel. A.M. Belevich (pers. comm., 1990) examined a rich complex of diatoms from samples of these strata collected from the lower part of the Tundrovaya River and from the piedmont at elevations ranging up to 200 m. These diatoms are Pliocene in age and typical of sea water with normal salinity. Attempts to date the Pliocene in the south were unsuccessful.

Quaternary deposits on the island consist of coarse clastic sediments: alluvial, proluvial (base of slope deltas), eluvial (felsenmeer) and colluvial (slope-wash) material. Coastal-marine sediments occur around the periphery of the island. The island has almost no glaciogenic deposits with the exception of minor accumulations associated with very recent basins.

Mammoth teeth, tusks and other bones are abundant in the Mamontovaya River and southwest island areas.

## STRUCTURAL GEOLOGY

### Introduction

The structural framework and internal structural characteristics of Wrangel Island have been determined from successive regional geological mapping expeditions as reported by Gromov and Kiryushina (1947); Til'man et al. (1964, 1970); Byalobzhesky and Ivanov (1969, 1971); Kameneva and Chernyak (1973, 1974); and Kameneva (1975). These reports have in turn been reviewed by Kos'ko (1984). There is little new information in the present account that has not been generally reported in these earlier publications. An attempt has been made to reconcile the full array of structural elements into a new kinematic model. Constraints imposed by this model have been considered in cross-section construction (Fig. 51).

Sedimentological observations provide additional information on tectonic history. For example, clasts of foliated rocks occurring in strata of Devonian through Permian ages provide evidence for both an earlier phase of regional metamorphism and strain, and a concurrent phase of uplift and syntectonic sedimentation. These types of data are summarized in 'Tectonic history' that follows. A note of caution follows from the previous statement: all structures, especially outcrop-scale structures such as foliation attitudes and minor folds encountered in the Wrangel Complex, have been analyzed within the context of a single, protracted, tectonic event of approximately Middle Jurassic to Early Cretaceous age. In fact, some of the smaller structures may have been generated during one of several earlier phases of deformation for which there is now only indirect sedimentological evidence, and some of the larger structures may have been generated during post-Early Cretaceous tectonic events.

### Structural provinces

Structural provinces of Wrangel Island include a northern coastal plain, a southern coastal plain and an intervening central uplift (Fig. 50). The northern coastal plain, also referred to as the Tundra Akademii, is exposed across the entire north side of the island from the mouth of the Medvezh'ya River in the west to Cape Uering in the east, and reaches a maximum width of approximately 30 km at longitude 179°W. This northern structural province is a low-lying terrain underlain by undeformed Tertiary and Quaternary sediments of both marine and terrestrial origin. This belt is believed to represent the southernmost updip limit of a upper Lower Cretaceous (middle to Upper Albian) through Quaternary sedimentary wedge that is linked to much thicker correlative deposits now preserved on the Chukchi Shelf and within the North Wrangel and Vil'kitskii/North Chukchi basins (Figs. 5, 6, 7b, 8; Kos'ko, 1984; Grantz et al., 1990).

The southern coastal plain is a much narrower (0–20 km) sedimentary apron exposed in two separate belts between Cape Blossom (in the west) and the mouth of the Nasha River (in the east). The southern coastal plain is also thought to represent the on-land portion of much thicker Cretaceous and Cenozoic strata preserved in the offshore; in the present case, the northern limit of South Chukchi (Hope) Basin (Figs. 5, 6, 7a, 8; Pol'kin, 1984).

The northern and southern coastal plains are separated by a continuous sublatitudinal belt of penetratively deformed Triassic and older rocks, here referred to as the 'central uplift'. The central uplift is an informal term that refers to the on-land, and exposed portion, of the more extensive Wrangel–Herald Arch. The core of the arch is a pre-Late Cretaceous "basement" complex that subcrops on the sea floor mostly in the direction of Lisburne Peninsula, western Alaska (Figs. 5, 8; Kos'ko et al., 1990; Grantz et al., 1990). The arch itself is likely a complex feature with both Late Cretaceous and inherited positive structural relief.

The largest structural features of Wrangel Island's central uplift include the Northern Anticlinorium, the Central Anticlinorium and the intervening Medvezh'ya Synclinorium (Figs. 50, 51). In map view, the generalized hinge line of the Central Anticlinorium describes an open, sinusoid curve that is sublatitudinal in trend, and convex to the south across the western and central part of the island, but convex and north-facing where it links with the west-northwest-trending Northern Anticlinorium. Lying between these two anticlinoria, the Medvezh'ya Synclinorium widens and plunges to the west and west–northwest, but terminates in the east at the intersection of the bounding anticlinoria on the Vostochnoe Plateau.

An internally complex belt of Triassic turbidites up to 20 km wide is exposed across nearly the entire southern third of the central uplift (Fig. 9). In the present interpretation, this belt is placed on the south-facing back-limb of the Central Anticlinorium. The width of this back-limb succession in many areas is greater than the entire width of the remaining older

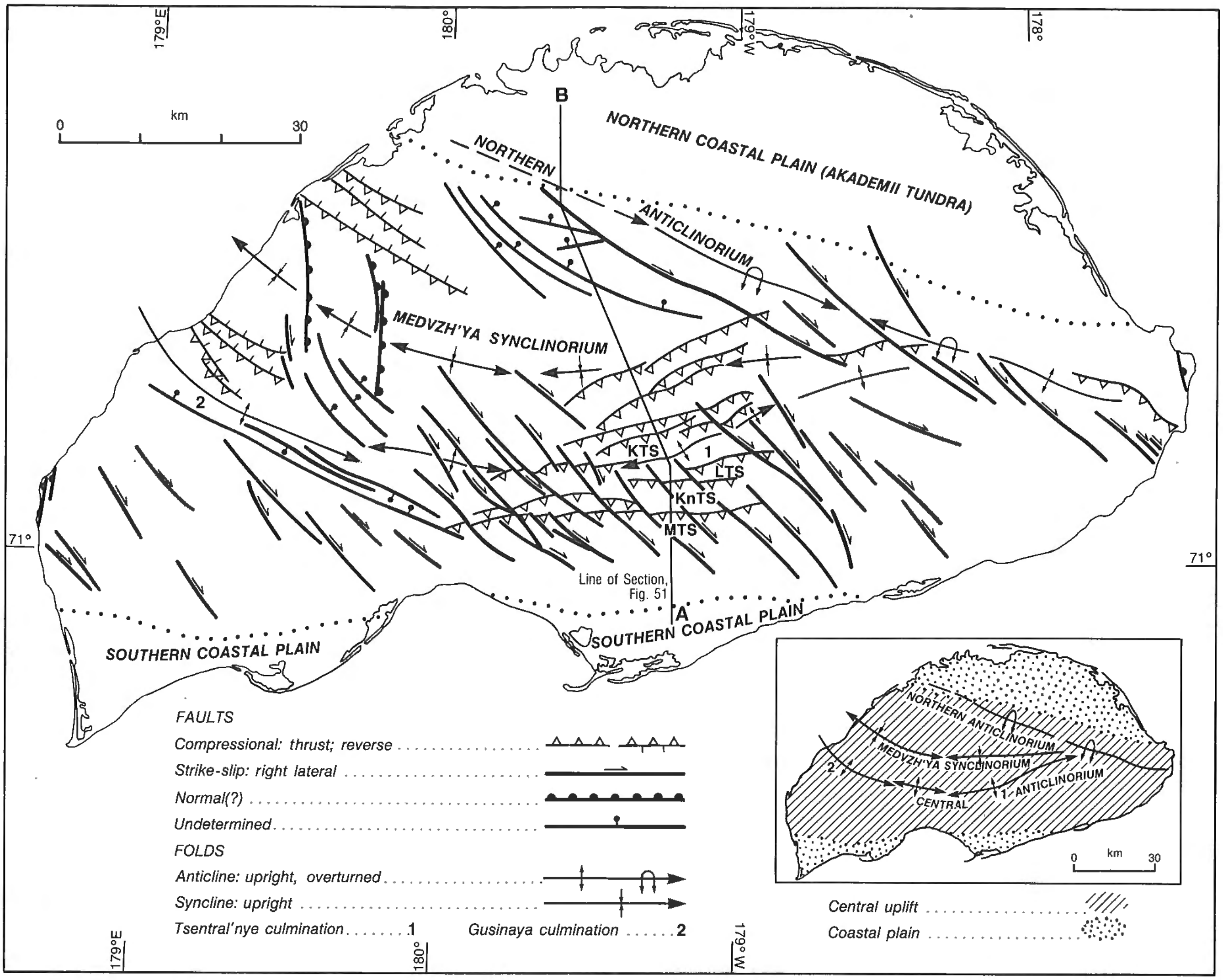


*Figure 50. Regional structural elements of Wrangel Island and location of the structural cross-section illustrated in Figure 51. MTS, Mineev thrust sheet; KnTS, Khishchnikov thrust sheet; LTS, Lager'nyi thrust sheet; KTS, Khrustal'nyi thrust sheet.*

rock packages exposed along the hinge and north limb of the anticlinorium. Thus the Triassic back-limb succession could be separated out as a fourth and distinct tectonic belt, but this approach has not been followed here.

Structural features common to all three tectonic belts of the central uplift include map-scale and smaller north-vergent folds and a penetrative south-dipping cleavage that is broadly coplanar with the local and regional fold system. The most tectonically rigid strata include much of the Wrangel Complex, and carbonate rocks of the $C_{1-2}$ Unit. Slate-rich intervals in the lower part of the $D_{1-3}$ Unit, in much of the $P_{1-2}$ Unit, and in the Tr Unit, are preferred levels of detachment (Fig. 51). Other through-going detachments are presumed to exist within slate-dominated intervals of the Wrangel Complex, and in evaporites locally documented in the $C_1$ Unit. Detachments in the Tr Unit are numerous between slate-dominated and sandstone-dominated units and are associated with intraformational folds.

Faults represent a fundamental and highly visible feature of the central uplift. The classification and distribution of these structures has been illustrated on a regional tectonic map of the island (Fig. 50 - interpreted from Fig. 9). Included here are: i) fold-parallel thrust faults, common over the hinge of the Central Anticlinorium in the middle of the island, and within the eastern half of the Medvezh'ya Synclinorium; ii) fold-parallel reverse faults, situated

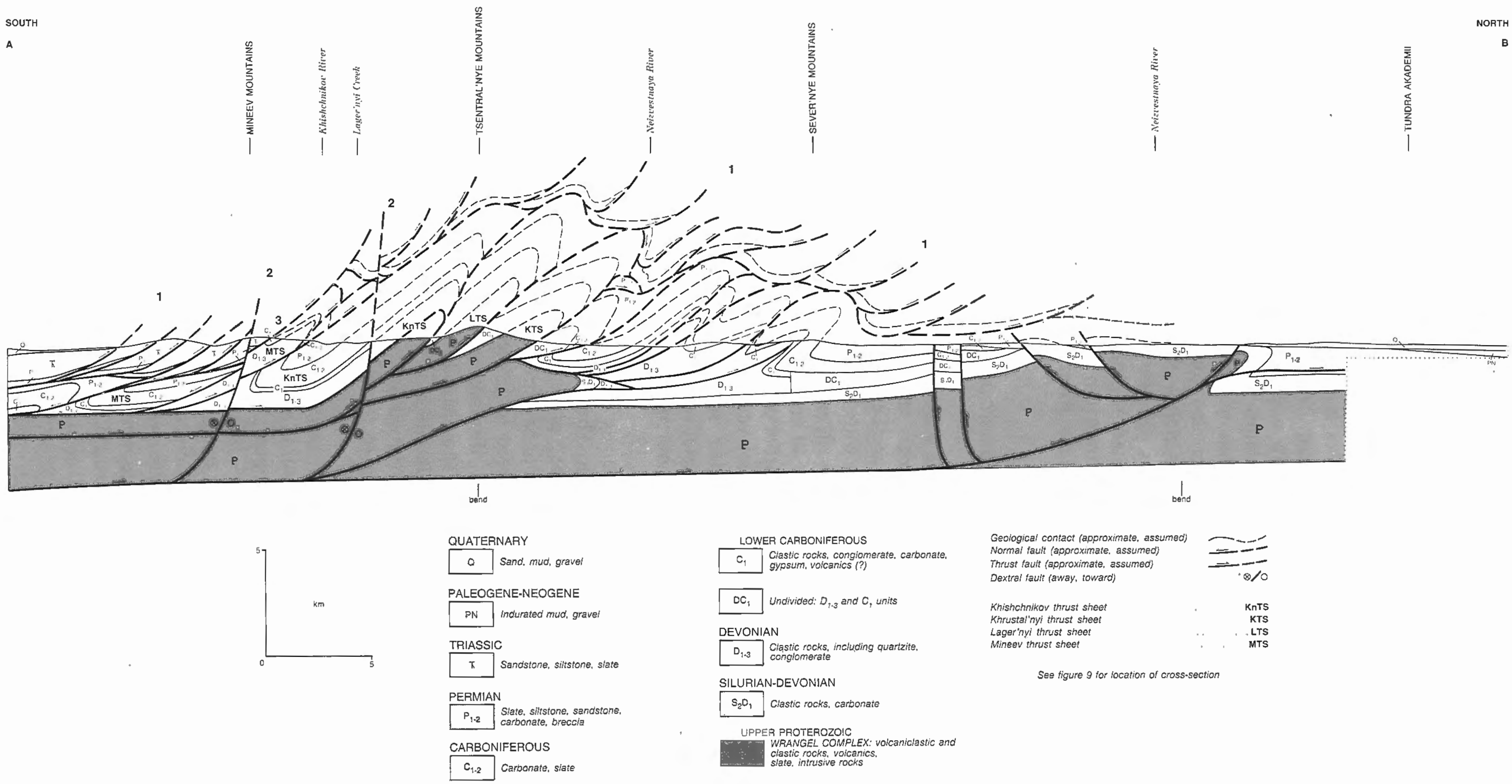


***Figure 51.*** *Structural cross-section through central Wrangel Island including the Tsentral'nye culmination, eastern Medvezh'ya synclinorium and northern anticlinorium of the Central Uplift, and extrapolated structural style beneath the northern and southern coastal plains (see Figs. 9 and 50 for section location).*

*1) Intraformational thrusts are common in the Triassic. Location of thrusts both in the outcrop belt and as projected above surface are strictly schematic and intended only to express probable structural style. 2) right-lateral faults are steep and are known to offset all other faults and all units including the Wrangel Complex. A deep level of detachment is likely. The actual level of detachment as illustrated is conjectural. 3) The sub-Triassic surface on the line of section is interpreted as a down-to-the-south normal fault detached on the Devonian and offset by strike–slip faults. An alternate interpretation is that this is a sub-Triassic disconformity. 4) Khrustal'nyi thrust sheet (KTS). 5) Lager'nyi thrust sheet (LTS). 6) Khishchnikov thrust sheet (KnTS). 7) Mineev thrust sheet (MTS).*

on the southern limb of the Northern Anticlinorium and along the southern edge of western Medvezh'ya Synclinorium; iii) an evenly spaced array of fold-oblique northwest-striking dextral strike–slip faults, mapped in nearly all areas of the central uplift; and iv) other faults of uncertain slip sense, including separate west–northwesterly striking and northwesterly striking, and northerly striking sets. The west–northwesterly and northwesterly striking set, found in the Gusinaya River basin and along the south-facing limb of the Northern Anticlinorium, may have experienced either reverse slip, dextral slip or an oblique slip combination of these motions. Apart from displaced formational contacts and dip angles of more than 60°, nothing else is known.

The northerly striking fault set occurs along the east and west coasts of the island and in the Bezymyannye Mountains. Like the unclassified faults, little is known concerning dip direction and slip sense. One possibility is that these faults are associated with late Early Cretaceous and younger extensional tectonism.

Additional specific structural characteristics of the two anticlinoria and intervening synclinorium are provided under separate headings, below.

### *Central Anticlinorium*

The Central Anticlinorium is a belt of convergent structural elements. Along its axial high, strata of Devonian and older age are exposed. This south-facing convex arc is also defined by a topographically elevated terrain that embraces western coastal cliffs in the vicinity of Cape Ptichii Bazar, hills in the drainage basin of the Gusinaya River, the Mamontovye and Tsentral'nye mountains, and the lower hills of the Vostochnoe Plateau lying in the drainage divide between the Klark and Naskhok rivers. In this last area, the Central Anticlinorium merges with the Northern Anticlinorium, from which point the combined high continues on to the east coast between capes Uering and Pillar.

Convergent structural elements in the Central Anticlinorium are almost exclusively north vergent. As a result, the north-facing limb of the high is a narrow belt dominated by scarp slopes above thrusts and by steep north-dipping or overturned south-dipping bedding attitudes. For the same reason, the axial trace of the high lies closer to the northern limit of the anticlinorium. The south limb, featuring shallow, south-dipping and upright bedding, is a much wider, dissected backslope underlain by a tectonically thickened stack of Triassic turbidites.

The oldest rocks are found along the hinge of the anticlinorium, with the principal exposures occurring within two structural highs, here informally referred to as the 'Tsentral'nye' and 'Gusinaya' culminations. The apex of the 'Tsentral'nye' culmination lies in the Tsentral'nye Mountains with exposures of Wrangel Complex in the core (Figs. 9, 50, 51). Plunge on the culmination is to the east toward the Vostochnoe Plateau and to the west beyond the Mamontovye Mountains. The second structural high, the 'Gusinaya' culmination, provides structural windows into rocks of Silurian and younger age (Figs. 9, 50). The full extent of this high is obscured to the west of the island by the waters of the East Siberian Sea. Eastward the culmination plunges to an axial saddle on the Central Anticlinorium situated in the headwaters of the Gusinaya River (Fig. 9).

### *The Tsentral'nye culmination*

At the scale of mapping, the Tsentral'nye culmination includes an assemblage of eight sublatitudinal to east–northeasterly striking thrusts, associated in most cases with hanging wall, north-vergent anticlines and footwall, north-vergent synclines. Thrusts range from 10 to 40 km in length with individual displacements on the order of 3 km or less. The greatest structural relief is displayed on the lowest thrust sheets. An impressive display of the thrust front is exposed where Khrustal'nyi Creek emerges from a canyon draining the north slope of the Tsentral'nye Mountains (Fig. 52). In this area, poorly exposed Carboniferous carbonate ($C_{1-2}$ Unit) underlies the low country to the north. The mountain front, rising abruptly from these plains, presents a resistant 1000 m thick stack of mylonitic Wrangel Complex lying on a thrust that is inferred to subcrop beneath recent alluvium. To the west, displacement on this thrust gives way to folding in the Mamontovye Mountains. Eastward, displacement is transferred to west-plunging, footwall, overturned folds and other footwall thrusts mostly lying to the northeast (Fig. 9).

A cross-section through the middle of the Tsentral'nye culmination crosses four of the eight mapped thrusts (Figs. 12, 51). While only these few have been examined in detail, the other mappable thrusts are believed to be similar in both gross and specific character. The drainage divide above the headwaters of the Khishchnikov River lies in Wrangel Complex near the thrust contact between the Khrustal'nyi and Lagernyi thrust sheets (Fig. 51). Foliation in the Lagernyi sheet dips to the south at 15 to 25°. Wrangel Complex is repeated a third time where the Khishchnikov thrust sheet has been emplaced

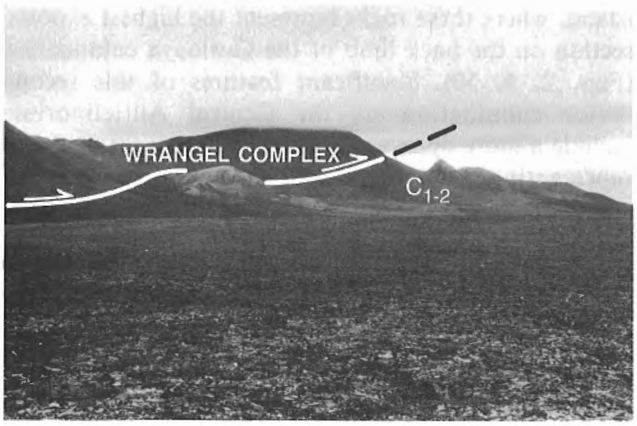


*Figure 52. Panoramic view to the west of the Khrustal'nyi thrust sheet near where Khrustal'nyi Creek emerges from the Tsentral'nye Mountains. Upper Proterozoic Wrangel Complex here has been thrust over Carboniferous carbonate. I.S.P.G. photo. 3865-4.*

*Figure 53. Crenulated Carboniferous slate in the immediate footwall of the Khishchnikov thrust sheet. Both the primary cleavage and crenulation cleavage dip to the south. Outcrop situated on the upper reaches of Lager'nyi Creek. I.S.P.G. photo. 2672-9.*

over an easterly thickening sliver of undivided $DC_1$ Unit carbonate and lesser amounts of coarse clastic rocks at the top of the Lagernyi sheet. Black slaty phyllite, occurring in the immediate footwall of the Khishchnikov thrust, display both a shallow, south-dipping cleavage and a transecting, steeply south-dipping crenulation (Fig. 53). The Khishchnikov thrust sheet is approximately 3000 m thick and includes essentially complete exposures of the entire Devonian through Upper(?) Permian stratigraphic section in the central part of the island. Typical bedding dips are southward at 25 to 45°. Cleavage angles are similar. North-vergent parasitic folds, especially common in the $C_1$ Unit, may be associated with bedding-parallel shortening on secondary detachment surfaces in $C_1$ Unit evaporites (Fig. 54). Steep cleavage-to-bedding intersections are associated with the hinge region of these minor folds; a feature also observed in parasitically folded areas of Permian slate high in the same thrust sheet (Figs. 41, 55).

The $P_{1-2}$ Unit is undoubtedly an important level of detachment because not only does it represent the footwall to the next and highest thrust sheet but it also represents the footwall and upper detachment on a lateral ramp emerging from beneath a separate imbricate to the west in the headwaters of the Somnitel'naya River.

The Mineev thrust sheet is the highest in the Tsentral'nye culmination and is encountered in outcrop along the lower Khishchnikov River (Fig 56). The hanging wall section exposed throughout the Mineeva Mountains includes some 600 m of recessive Devonian and Carboniferous siliciclastic rocks and lesser carbonate, and an uncertain thickness of resistant Triassic sandstone and slate, possibly in excess of 1000 m thick. The immediate hanging wall of the thrust is a 60 to 80 m thick section of tectonically brecciated dolomite locally transected by quartz veins (Fig. 57). These rocks and the structurally overlying siltstone and sandstone are overturned to the south at 70 to 80°. Cleavage dips at a shallower angle to the south, and a steep southerly dipping crenulation has been noted in slate beds near the thrust. All these observations considered together suggest that the hanging wall of the Mineeva Mountains thrust is a regional-scale north-vergent anticline (Fig. 51). A high scarp slope on the upright, southerly dipping limb of this anticline is exposed along the north face of the Mineeva Mountains east and west of the Khishchnikov River. This face presents a panoramic view of the controversial sub-Triassic surface, beneath which more than 1000 m of Carboniferous carbonate and Permian slate has been cut out (Figs. 47, 56). On the cross-section, the sub-Triassic surface is interpreted by JCH as a down-to-the-south listric normal fault detached on Devonian mudrocks and offset by subsequent strike-slip faults. (MPC and MKK view this as an unconformable sub-Tr Unit surface - see discussion under Tr Unit-Contacts).

An evenly spaced array of steep faults is oblique to the regional fold-thrust system of the Tsentral'nye culmination. These oblique faults possess a consistent N40°W through N50°W strike direction and are

*Figure 54. Small-scale fold in Lower Carboniferous strata ($C_1$ Unit). Fold is overturned to the north (left). Outcrop-scale folds are common in the sandstone and intercalated gypsum within the medial part of the Khishchnikov thrust sheet. Outcrop is situated near the headwaters of the Khishchnikov River. I.S.P.G. photo. 2672–31.*

commonly observed to offset strata and many of the thrusts within the Tsentral'nye culmination. Some of these oblique faults also extend into adjacent areas of the Medvezh'ya Synclinorium. Horizontal separations defined by displaced formational contacts and pre-existing thrusts are consistently right-lateral in sense. Apparent horizontal displacements range up to several hundred metres. A notable example is encountered in the headwaters area of the Khishchnikov River (Fig. 28). Beds of Carboniferous evaporite, sandstone and carbonate have been rotated to near vertical near the fault. Implied sense of drag is also consistent with the right lateral offset of bedding across the fault. Slaty rocks exposed near the covered fault trace are intensely fractured and slickensided. Intercalated sandstone beds are boudinaged. Tectonically dismembered quartz veins are common and limonitic staining is pervasive. Several of these steep faults have been intersected along the line of cross-section (Fig. 51). Dip separation is south side down, with the detachment level at a hypothetical depth within the Wrangel Complex.

### The Gusinaya culmination

The tectonically thickened stack of Triassic turbidites exposed in the Mineeva Mountains also extends into the Yevstifeyeva Mountains on the west coast of the island, where these rocks represent the highest exposed section on the back limb of the Gusinaya culmination (Figs. 2, 9, 50). Significant features of this second major culmination on the Central Anticlinorium include a more open style of folding, with thrust faults representing a less conspicuous mechanism for the accommodation of the shortening. Typical bedding attitudes range from 20°S on the south limb of the culmination to 20°N on the north limb. Cleavage is generally subparallel to bedding, and at one locality on the north bank of the Gusinaya River, dips to the south at 20 to 40°. The maximum stratigraphic section exposed by folding in the Gusinaya culmination (several thousand metres) is also less than in the

*Figure 55. Interbedded brown weathering quartz sandstone and buff weathering siltstone of the $C_1$ Unit. This talus boulder is derived from an adjacent outcrop exposed in the axial region of a mesoscopic fold. Note the high cleavage-to-bedding intersections. Outcrop is near the headwaters of the Khishchnikov River. ISPG photo. 2672–19.*

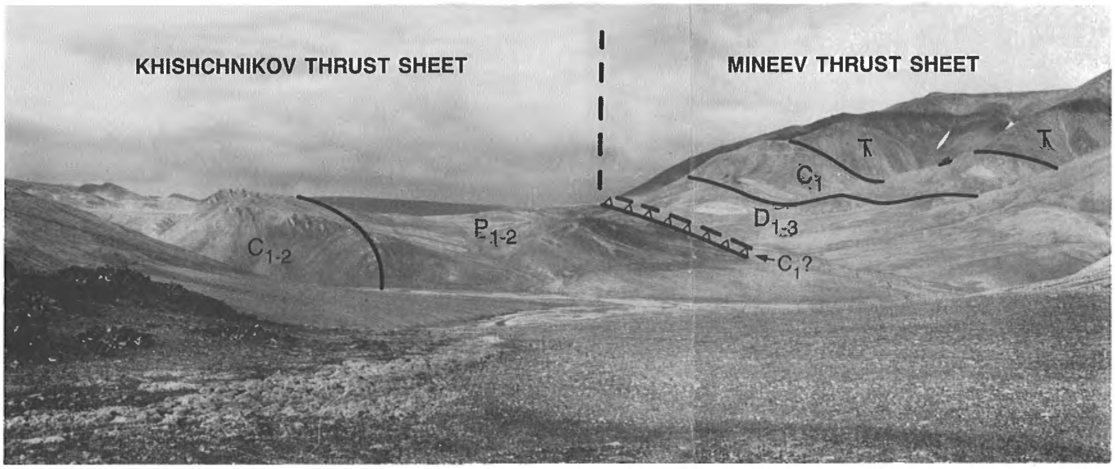


*Figure 56. Panoramic view (looking east) of the upper part of the Khishchnikov thrust sheet (left) and the lower part of the Mineev sheet (in the Mineeva Mountains, right). More than 1000 m of Carboniferous and Permian strata have been cut out either by erosion or by normal faulting beneath the Triassic within the Mineev thrust sheet. I.S.P.G. photos. 3865–10, 3865–11.*

Tsentral'nye culmination (about 5000 m). A major fault mapped along the middle and upper Gusinaya River represents only one of several tectonic elements linking the Gusinaya and Tsentral'nye culminations through an intervening saddle (Figs. 9, 50). This fault also bisects the Gusinaya culmination into two subsidiary highs, with apices situated north and south of the river. Vertical separation across the fault is up to perhaps 1000 m, south side up, and although some horizontal slip is possible, the map pattern is consistent with a reverse sense of motion. Other faults have been mapped in the Bezymyannye Mountains along the north limb of the Gusinaya culmination. These faults display an apparent dextral sense of separation but are also associated with mappable fault-parallel subsidiary folds. This implies a possible kinematic history that includes both convergence and strike-slip. Considering all these facts together, total horizontal shortening measured across the anticlinorium would appear to decrease from east to west from a maximum in the Tsentral'nye Mountains. Less certain is the extent to which horizontal shortening has been replaced westward by fold-parallel strike-slip. Estimates of shortening as obtained from the line of section (Fig. 51) are considered separately in this account (see on).

Impossible to take into account, at the present scale of mapping, is shortening accomplished on outcrop-scale structures that range up to several kilometres in wavelength. A traverse along the west coast of the island south of the mouth of the Gusinaya River demonstrates the problem. An east-plunging, open, upright fold pair, possessing a wavelength of 4 km, includes a shallow, synclinal belt of Permian strata and an anticlinal nose of biohermal Carboniferous rocks at Cape Ptichii Bazar (Fig. 9). Southward, a 60 m thick interval in a medial portion of the Permian section is repeated by north-vergent thrusting and folding with individual fold wavelengths on the order of 50 to 100 m (Fig. 58).

The Triassic strata, which present a 20 km wide south-dipping homocline at the scale of mapping, are seen in detail to have a much more complex internal style of deformation. A south-dipping spaced cleavage is seen in all exposures. Cleavage refraction is demonstrated between competent sandstone and incompetent intervening slate (Fig. 48). Axial planar cleavage fans are associated with minor north-vergent folds. Together these features provide a kinematic link between cleavage development and horizontal shortening by folding. Although there are internally coherent stratigraphic intervals up to several hundred metres thick in the Triassic, intraformational folds and shallow-dipping minor thrusts are common. The magnitude of shortening within the Triassic package, however, will remain unknown until a reliable estimate of primary stratigraphic thickness is available. To illustrate this point, the maximum implied thickness for a 20 km wide belt of Triassic rocks with a dip of 20° is about 6800 m. If the belt has been doubled in thickness by some form of internal shortening such as a thrust duplex, then the implied horizontal shortening for the initial 3400 m thick succession is at least 10 km. Horizontal shortening would be proportionately increased by a decreased primary depositional thickness but would also be reduced by a decreased dip angle of strata.

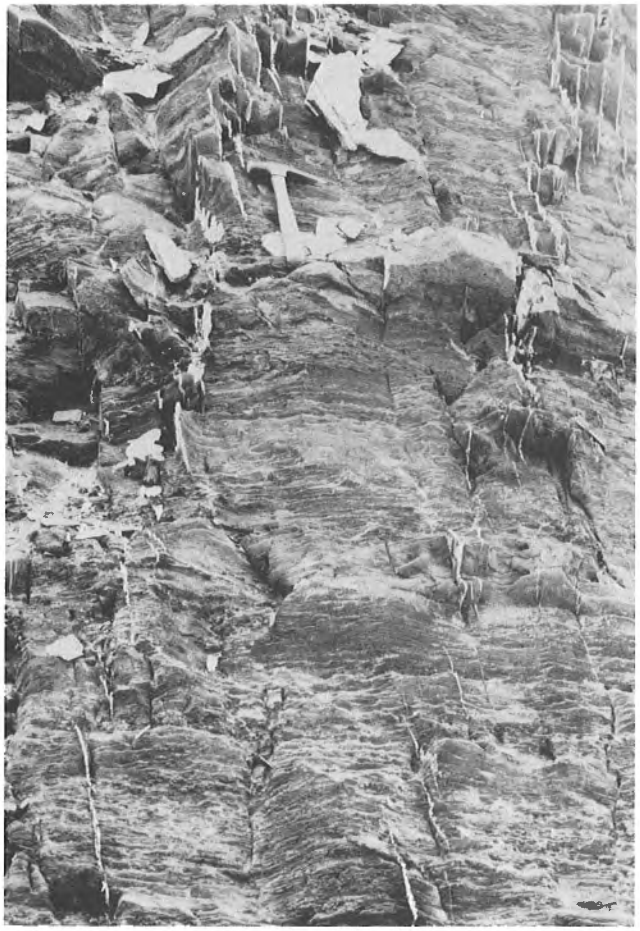

*Figure 57. En-echelon fracture fillings in $P_{1\text{-}2}$ siltstone. I.S.P.G. photo. 3819-9.*

The preferred interpretation of structural style for the Triassic panel is illustrated on the cross-section (Fig. 51). Thrusts have repeated the Triassic section as a result of shortening originating on a detachment level in the Permian. Although the exact location of thrusts remains speculative, the style is consistent with field observations. Thrust-repeated Triassic must have extended over the hinge of the Central Anticlinorium prior to uplift and erosion.

### *Medvezh'ya Synclinorium*

The eastward convergence of the Central and Northern anticlinoria in the headwaters area of the Naskhok and Klark rivers also marks the eastern limit of the Medvezh'ya Synclinorium. Like the tectonic belt to the south, the synclinorium has a convex south-facing axial trace that plunges roughly toward N95°W in the Neizvestnaya drainage basin and toward N60°W in the Bezymyannÿe Mountains. The bounding anticlinoria continue to diverge even beyond the west coast of the

*Figure 58. Outcrop-scale north-vergent anticline in medial Permian strata, sea coast south of Cape Ptichii Bazar. The size of this fold suggests a very shallow level of detachment, possibly within mudrocks at the base of the Permian section. I.S.P.G. photo. 2672-32.*

island. Therefore the west limit of the synclinorium is farther to the northwest in the offshore.

In detail the Medvezh'ya Synclinorium is divisible into eastern and western portions differing significantly from each other in internal styles of deformation. The line of separation is drawn along a northeast-trending high underlain by Carboniferous carbonate that crosses the synclinorium from the Mamontovye Mountains to the southern slopes of Mt. Tundrovaya. The western portion of the synclinorium is a saucer-shaped depression open to the northwest and underlain by gently dipping Triassic and older rocks (Fig. 9). The extent of deformation in this area remains unstudied although a series of northerly striking faults have been mapped transecting the trend of the synclinorium. Other, northwesterly striking faults lying in the headwaters of the Mamontovaya River occur both on the deformed north-facing limb of the Gusinaya culmination and within the synclinorium.

The eastern half of the synclinorium is more complexly deformed. Important elements of this deformation are northwesterly vergent thrusts up to 18 km in length with limited displacement, and kinematically associated hanging wall and footwall folds overturned to the north (Fig. 59). Hanging wall section above the thrusts includes pre-Carboniferous felsic and mafic volcanic rocks and Carboniferous coarse clastic rocks (Fig. 32). Footwall strata include these rocks and also mid-Carboniferous $C_{1\text{-}2}$ carbonate. Vertical stratigraphic separation probably does not exceed 1000 m. The trend and strike directions of these various structures (N45–60°E), is

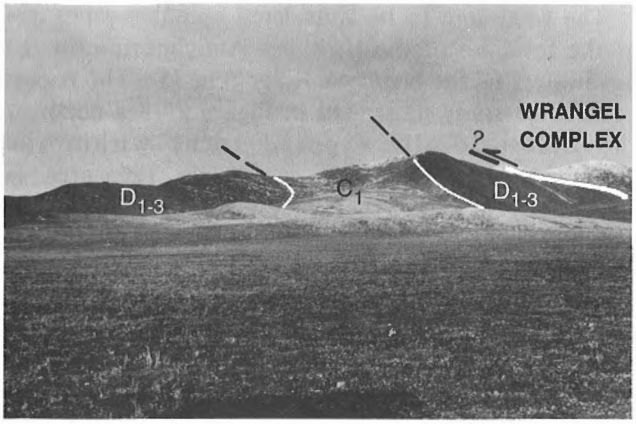


*Figure 59. View looking to the east of map-scale folds overturned to the north. These exposures are situated in the Carboniferous and Devonian rocks of the eastern Medvezh'ya Synclinorium in the upper reaches of the Neizvestnaya River. The Wrangel Complex (in the higher hills at far right) lies within the Tsentral'nye culmination and may be in thrust contact with footwall Devonian strata. I.S.P.G. photo. 3865-6.*

demonstrably oblique to the sublatitudinal trend of the synclinorium (N85°E). The second-order folds and thrusts of the eastern Medvezh'ya Synclinorium, together with the thrust sheets of the Tsentral'nye culmination, define an easterly diverging fold-thrust fan. The western limits of this fan fall short of the point of convergence between the Northern and Central anticlinoria. The subsurface linkage of thrusts between the eastern Medvezh'ya Synclinorium and the Tsentral'nye culmination is illustrated in the cross-section (Fig. 51). Thrusts arising out of detachments in the Wrangel Complex are linked to slip on a shallow décollement in the Devonian section. Folds and thrusts in the synclinorium lie on the Devonian detachment, and together, the entire fold-thrust bundle has been crossfolded.

## *Northern Anticlinorium*

Ranges of low hills dissected by northward-draining river systems represent the only topographic expression of the Northern Anticlinorium. The axial trace of the high is only known with certainty in the northeast, where Devonian and Carboniferous siliciclastic rocks are exposed in the hinge. The trend of the anticlinorium in this area is N65–72°W and is traceable in felsenmeer across the Vostochnoe Plateau and headwaters of the Naskhok River. The hinge is last observed in the interfluve between the Neizvestnaya and Krasnyi Flag rivers, where it is overlapped with profound angular unconformity by Quaternary deposits of the northern coastal plain. Separate exposures in the Mount Drem-Khed and Neizvestnaya River areas are complexly deformed portions of the generally south-facing and upright limb of the Northern Anticlinorium, and include older (Silurian) rocks not seen in the northeast. These preliminary observations suggest that the plunge on the culmination is toward the east-southeast from an unknown point of closure, subcropping perhaps north, northeast or northwest of Mt. Drem-Khed on the sub-Cenozoic unconformity surface beneath the northern coastal plain.

The exposures at Mt. Drem-Khed and Mt. Maly Drem-Khed represent a part of a locally developed, southeasterly-plunging syncline displaying very gently dipping bedding attitudes in the exposed Silurian and Devonian section. The relation of this structure to the Triassic deposits nearby within the Medvezh'ya Synclinorium is obscured by Quaternary alluvium, but an intervening fault would appear likely (shown as a fault on Fig. 50). Farther east, however, $S_2D_1$ Unit rocks are exposed unconformably beneath the $P_{1-2}$ Unit.

Stream-bank exposures along the Neizvestnaya River present a more complex pattern of local deformation (Fig. 40). Permian strata in this area rest disconformably on Silurian carbonate with thick sedimentary breccia preserved above the sub-Permian erosion surface. These rocks have been folded together and offset by both sublatitudinal and sublongitudinal faults, generally at scales generally too small to be observed on either the regional-scale map or the cross-section. A hundred-metre scale isoclinal anticline has been documented at the confluence of the Lemmingovaya and Neizvestnaya rivers. Upright and overturned limbs dip to the southwest at 45°.

Smaller outcrop-scale folds, featuring an interbedding of $C_{1-2}$ Unit limestone and slate, can be considered typical of the style of shortening at all scales (Fig. 60). Individual bedsets of slate or limestone range from 30 cm to 1.4 m. Fold vergence is consistently to the north in all three outcrops. Backlimbs dip south at 15 to 40°. Forelimbs are commonly vertical or overturned. Both limestone and slate display axial thickening. The extent of thickening ranges up to 270 per cent in some limestone bedsets and up to 400 per cent in the intervening slate. Separation of the footwall syncline and hanging wall anticline is displayed in only the most advanced stages of shortening (Fig. 60). The development of a thrust along the plane of inflection on the overturned limb is accompanied by hinge zone brecciation of relatively competent carbonate beds and the tectonic mixing of comminuted slate and finer limestone fragments.

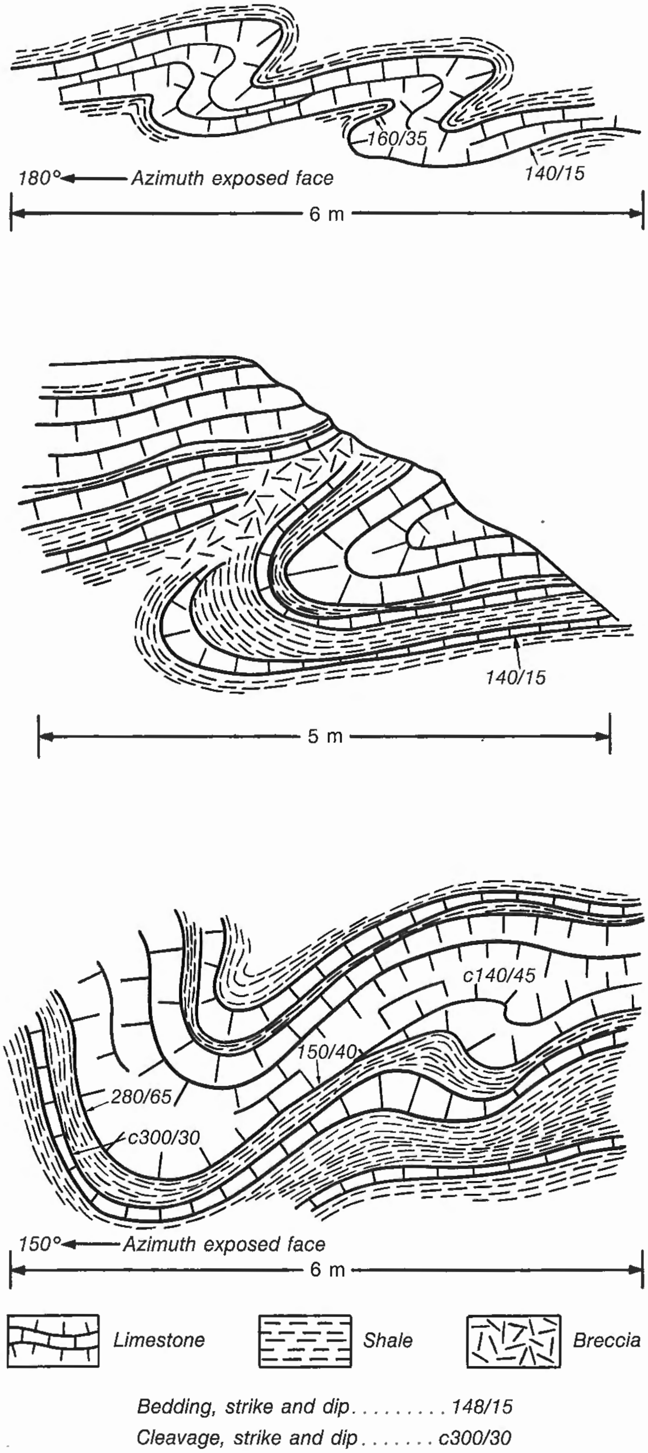


***Figure 60.** Sketches of minor folds in Carboniferous slate and carbonate, lower Neizvestnaya River area.*

The final area to be considered contains exposures of the forelimb of the Northern Anticlinorium in the headwaters of the Naskhok River (Fig 35). The region of detailed study illustrated in Figure 35 lies north of the oldest locally exposed rocks within the anticlinorium. The entire section in this area is structurally inverted. The oldest forelimb strata are assigned to the DC$_1$ Unit and are exposed in felsenmeer at higher elevations to the south. C$_{1-2}$ Unit carbonate structurally underlies the DC$_1$ Unit and dips to the south at overturned angles of 10 to 30°. This section is in turn underlain by still younger Permian strata, and Triassic rocks may be exposed still farther to the north. Exposures of these youngest rocks are poor and it is not known for certain whether they lie on the upright or overturned limb of the larger structure.

Minor folds are known throughout this area and east as far as Cape Uering. North-facing forelimbs are typically overturned and both forelimbs and backlimbs dip to the south at 30 to 50°.

Large faults striking N55–80°W, both parallel and marginally oblique to the trend of the Northern Anticlinorium, are known in the Mt. Tundrovaya and medial Neizvestnaya drainage basin area. Others are known near Mt. Drem-Khed, and a thrust near Cape Pillar places Devonian over Permian. Dip direction and angle on most of these faults remains unknown. Mappable offsets of formational contacts range up to hundreds of metres in directions consistent with movements involving either normal faults or south-directed thrusts or reverse faults.

As in other areas of the island, cleavage development in the Northern Anticlinorium is ubiquitous in all pre-Cenozoic rocks. In the Krasnyi Flag area, cleavage has been observed subparallel to the plane of bedding and, in one open, upright fold with limb dips of about 20°, both bedding and cleavage have been buckled.

In spite of the simplicity of the cross-section across the Northern Anticlinorium (Fig. 51), the structural observations collected from the Neizvestnaya and Naskhok rivers area and elsewhere provide sufficient evidence to suggest that the Paleozoic rocks in even the most northerly exposures have undergone a style and scale of convergent orogenic shortening comparable in many ways to that of the topographically more elevated and deeply dissected areas of the Central Anticlinorium. Although the rocks of the Medvezh'ya Synclinorium and Northern Anticlinorium were previously considered part of a foothills-type tectonic belt to the "front ranges" of the Tsentral'nye Mountains (Cecile and Harrison, 1987), it is now appropriate to consider the entire Precambrian through

Triassic succession of the central uplift as being part of a resurrected and deeply eroded window into the internal portion of a peneplained Mesozoic orogenic belt, the bulk of which must underlie thick Albian and younger sedimentary cover of the South Chukchi, North Wrangel and Vil'kitskii/North Chukchi basins (Figs. 5–8; Pol'kin, 1984; Kos'ko, 1984; Grantz et al., 1990).

## Estimates of horizontal shortening

Restored bed length of the $C_{1-2}$ Unit as obtained from the line of section (Fig. 51) is approximately 69 km. This includes strata within the folds and thrusts of both the Tsentral'nye culmination and eastern Medvezh'ya Synclinorium. Present distance is about 40 km, thus the implied horizontal shortening is 29 km. These strata are now preserved in an outcrop belt, the width of which is 58 per cent of the original belt width at the time of sedimentation. In other words, deformation has reduced the width of the belt by a distance equal to 42 per cent of the undeformed width. Not taken into account in this estimate is additional bed-parallel shortening by cleavage dissolution and related features of horizontal strain as observed within conglomerate clasts, corals, sedimentary load structures and other primary depositional phenomena.

As mentioned previously, cleavage and various scales of overturned folds continue to the northern limit of exposures, and there is no reason to think that the deformation does not continue farther north beneath younger cover. In view of uncertainties in the nature of this northern deformation, the shortening estimates for the upper Paleozoic strata (quoted above) do not take into account the structures within the Northern Anticlinorium.

Horizontal shortening is believed to decrease along strike both to the east and west of the Tsentral'nye Mountains.

## Summarized kinematic model

It is possible that the various anticlinoria, folds, thrusts, oblique faults and cleavage formed as distinct tectonic elements. Alternatively, these features may have formed during a single, protracted, orogenic event. For example, the existence of axial planar cleavage fans about minor folds suggests a simultaneous development of both small folds by bedding parallel shortening, and bedding orthogonal mineral dissolution along cleavage planes. The development of both outcrop- and map-scale folds is accompanied in the earlier stages of shortening by the progressive rotation of the axial plane and the overturning of the forelimb. The later stages of shortening appear to result in the complete attenuation of the forelimb by thrusting, commonly accompanied by brecciation and mobilization of silica into extensional void space. The late orogenic slip on large thrusts is also confirmed by the association of these faults with the development of a localized second-generation crenulation of the first-generation axial planar cleavage. Likewise, map-scale northwesterly striking faults oblique to most folds are also observed to offset the map-scale thrusts. This suggests development of these dextral strike–slip faults during only the latest stages of deformation. Nevertheless, a viable kinematic model for the central uplift involves a temporal overlap of strike–slip and horizontal shortening.

As well as the interpretations listed above, the following four-stage kinematic scheme for Wrangel Island's central uplift is also based on the Canadian Rocky Mountain fold-and-thrust belt model of Bally et al. (1966) in which detachments and associated reverse faults and folds are thought to young from top to bottom in a sedimentary pile. Structures are also thought to be oldest in the internal part of an orogen and young toward the foreland.

During the first orogenic stage, horizontal stresses are transmitted along a north-northwest–south-southeast-trending axis through the undeformed sedimentary succession. The resulting deformation produces minor folds (smaller than map scale) and shallow intraformational detachments. Progressive shortening causes rotation of axial planes, overturning of forelimbs and the development of a penetrative axial planar cleavage. Typical first-stage structures include intraformational folds: i) in the $P_{1-2}$ and Tr units south of Cape Ptichii Bazar; ii) in the $C_1$ Unit in the headwaters of the Khishchnikov River; and iii) in the $C_{1-2}$ on the lower Neizvestnaya River. The thrusts, illustrated on the cross-section (Fig. 51) in the Triassic and thought to be detached in the Permian, could also be considered first-stage structures.

The second orogenic stage overlaps the first in time and is characterized by map-scale folding involving more than 3000 m of stratigraphic section. These folds develop into overturned and recumbently folded sheets later in stage two. Included here are the topographically elevated folds of the Tsentral'nye Mountains, the lower relief folds of the Neizvestnaya River basin and the broad, open folds of the Gusinaya River basin. As the transmitted horizontal stresses are directed along a north-northwest-trending axis, horizontal shortening is greatest along planes of weakness orthogonal to this direction. Thus shortening is greatest in the fold–thrust fan across and north of the Tsentral'nye Mountains. Planes of weakness oblique to the principal tectonic transport direction, as in the Gusinaya culmination, have accommodated transmitted stresses by a combination of folding and oblique dextral strike–slip. The implication of stage two tectonics is that outcrop-scale folds and first-phase axial planar cleavage fans must be refolded about map-scale second-phase fold axes. Apart from the single example of a folded cleavage in an outcrop-scale minor fold in the Krasnyi Flag River area (see above), this relation has not been adequately confirmed by structural observation and measurement.

The third stage of deformation is continuous with the second stage and involves separation of map-scale footwall synclines and hanging wall anticlines along map-scale inflection plane thrusts. This point is emphasized on the cross-section (Fig. 51) in which intraformational stage-one thrusts in the Triassic (detached in the Permian) have been refolded by stage-two folds and stage-three thrust sheets detached in the Devonian strata and upper Wrangel Complex. The third stage of deformation is attended by tectonic brecciation and silicification of resistant beds such as those documented in the hanging wall Carboniferous dolostone of the Mineev thrust west of the Khishchnikov River. The third-stage thrusts also produce a peripheral crenulation cleavage that is a mesoscopic expression of the refolding of earlier cleavage.

The fourth stage produces a map pattern of dextral strike–slip deformation recorded on northwesterly striking tectonic elements, and during this stage shortening is maximized by folding and thrusting on a regional-scale, northeasterly trending restraining bend in an overall dextral transpressive tectonic setting.

This fourth stage of deformation produces the broadest scale of folding; specifically, the development of the Northern and Central Anticlinoria and the intervening Medvezh'ya Synclinorium. The fourth stage is also interpreted as including the proliferation, from the deepest structural levels, of right-lateral strike–slip faults, all of which offset and hence postdate stage-three thrusts and stage-two map-scale folds. The unproven implication of fourth-stage deformation, illustrated on the cross-section (Fig. 51), is that overturned second-stage folds and associated stage-three thrusts have been broadly refolded as a result of thrusts propagating out of a through-going deep-seated décollement situated at the lowest levels in the Wrangel Complex. Broad-scale deformation associated with stage four is consistent with the observation that the greatest regional uplift, found along sublatitudinal parts of the Central Anticlinorium, has been produced by a southerly directed axis of tectonic transport.

The kinematic model also places constraints on the timing of extension-related movement on the hypothetical normal fault lying within the Mineev thrust sheet. Slip has caused south-directed gravitational sliding of stage-three folds. However, this post-stage-three extensional slip surface has also been offset by stage-four dextral faults.

This kinematic model does not consider the distinct possibility that major structural trends may have been influenced by a pre-existing anisotropy. The trend of most Paleozoic strata to change from carbonate and/or clastic, shallower water facies to slate facies from the northwest to the southeast are one form of internal anisotropy. One consequence of this may be the stack of east- and northeast-trending thrust faults in the Central Anticlinorium. The predominant southerly dip of thrusts and related fold planes may be the shallow crustal response of the Paleozoic sedimentary package to the existence of a basinward-dipping (southerly) anisotropy, bedding surfaces, and northward reductions and discontinuities in detachment surfaces associated with the facies changes noted above. The curvilinear and sublatitudinal trend of the second-order folds and thrusts may similarly be superimposed on Paleozoic depositional facies transitions of comparable orientation. The oblique system of faults may have been generated within a universal N40–50°W-striking bedrock fabric within and/or beneath the Wrangel Complex.

Timing of the four kinematic stages invoked to explain the major structural elements of the central uplift are known to postdate the Triassic Unit but predate the development of the peneplain surface now covered by Cenozoic deposits of the northern and southern coastal plains. Contractional uplift and erosion of the Wrangel–Herald Arch can be considered synchronous with the accumulation of foredeep deposits lying north and northeast of the arch within the North Wrangel and Vil'kitskii/North Chukchi basins. The seismic profiles presented by Grantz et al. (1990) reveal a southward component of thickening in the wedge of pre-Upper Cretaceous seismic units believed to be approximately Aptian–Albian (late Early Cretaceous) in age (Fig. 7b). Southward thickening of this wedge is attributed to the derivation of the component sediments from ancestral orogenic highlands of the Wrangel–Herald Arch, an orogenic event that may have created the principal contractional and dextral strike–slip elements of the central uplift.

Some of the map-scale structural elements of the central uplift do not fit the proposed kinematic model. North-striking faults near the east and west coasts of the island may be relatively young features. Conceivably, these are normal (extensional) structures, in part responsible for the differential uplift of the island in the Cretaceous and/or Tertiary with respect to adjacent parts of the Wrangel–Herald Arch that lie in the offshore to the west, east and southeast. Some of the faults in the Gusinaya culmination may also not fit into the proposed model. This is due primarily to a lack of knowledge concerning fault attitudes, sense of slip and the kinematic relation of these features to the origin of the culmination.

Earlier phases of deformation, implied by the existence of foliated clasts within various Paleozoic syntectonic conglomerates, provide a more complete picture of tectonic history of the Wrangel Island area. These observations are summarized in the 'Tectonic history' section (to follow).

## METAMORPHISM

In earlier accounts of the geology of Wrangel Island, much significance was placed on the observation that the metamorphic grade of the rocks of the Tsentral'nye Mountains was significantly higher than that of the fossiliferous strata typical of the upper Paleozoic. Gorodinsky (1964) went so far as to assign a Proterozoic age to the assumed higher grade succession based solely on this distinction. Kameneva (1975) also hypothesized a clear distinction between the slate, schist and marble of the Tsentral'nye Mountains and the shale, limestone and sandstone of the Phanerozoic. For the present account, thin sections were analyzed and XRD mineral identification made from a representative suite of samples from all units, in an attempt to constrain the level and variation of metamorphic grade.

Field classification would label the pelitic rocks of all ages as either slate or phyllite. Black argillaceous rocks of this description within the Triassic and Permian units possess either a dull (commonly plumose-textured) appearance on cleavage planes, or a very weak phyllitic sheen, the individual mineral grains not apparent to the unaided eye. Individual mineral grains, apart from the occasional detrital quartz, are also usually indistinguishable in thin section. Black pelites are also common within rocks of Devonian and Carboniferous ages and are at least locally present within the Wrangel Complex. These rocks are labelled as either slate or phyllite. The slate invariably possesses a distinct phyllitic sheen. In these rocks, individual flakes of muscovite to 0.1 mm are identifiable in thin section. Nevertheless, primary sedimentary textures such as flat and ripple crosslamination are present within all units, although preservation is best within the Phanerozoic succession. An assemblage including muscovite–chlorite–quartz–albite was recognized from XRD analyses.

The psammo-pelitic rocks, common in units of Devonian through Triassic age, have a coarser mineral assemblage more readily recognized in thin section. Hand specimens are either dull coloured or display a greenish, tan, or grey, weakly phyllitic sheen on argillaceous partings. $C_1$ Unit siltstone from the headwaters of the Khishchnikov River contain microscopic assemblages of chlorite, muscovite, quartz and albite with lesser hematite. Grain sizes range up to 0.2 mm. A very fine grained Triassic sandstone from the Mineeva Mountains also possesses a microscopically visible aggregate of chlorite, muscovite, quartz and plagioclase with individual grains to 0.15 mm.

Immature conglomerates of Devonian and Carboniferous age from the Tsentral'nye Mountains (Khishchnikov River) and Mineeva Mountains (Somnitel'naya River) also possess a significant matrix component of argillaceous material and equivalent mineral assemblages. In these rocks, metamorphic grain sizes are significantly larger, with individual chlorite and muscovite flakes commonly ranging up to 0.2 to 0.5 mm. Quartz and albite are also common. $C_1$ Unit conglomerate and fossiliferous argillaceous limestone from the headwaters of the Khishchnikov River occur in the footwall of a major thrust. In this position they lie structurally between Wrangel Complex strata. The mineral assemblage in the conglomerate includes chlorite, muscovite, quartz and albite. The argillaceous limestone contains calcite, quartz and muscovite; the latter in microscopic flakes to 0.2 mm. The limestone also contains well preserved body fossils (crinoids).

The felsic to intermediate plutonic rocks of the Wrangel Complex commonly contain secondary assemblages of quartz, albite and muscovite. Some plutonic rocks contain primary biotite. These rocks are comminuted and crushed and smaller biotite anhedra are present. Most of us interpret these as fragments broken from primary biotite; however, one of us (BGL) interprets them as secondary. Mafic plutonic rocks possess an assemblage of chlorite, epidote, plagioclase and actinolite with secondary apatite and ilmenite. Anorthite content of the plagioclase determined optically is in the $An_{5-10}$ range and therefore must be considered true albite.

According to the evidence presented above, the metamorphic grade of all the rocks examined of all ages can not be higher than lower greenschist facies. The onset of amphibolite-grade metamorphism should be marked by the appearance of cordierite or staurolite in pelites and of hornblende and oligoclase in mafic rocks. None of these minerals are recognized in any of the rocks examined. The transition from lower greenschist to upper greenschist is usually taken at the first appearance of secondary biotite at the expense of muscovite and chlorite in psammo-pelitic and felsic to intermediate plutonic rocks. The apparent absence (see note above) of secondary biotite from the Wrangel Complex and all Phanerozoic strata, therefore, rules out the existence of upper greenschist facies metamorphism.

Less certain is the lower limit of metamorphic grade implied by the various mineral assemblages. For mafic rocks, actinolite and zoisite appear at the expense of pumpellyite, quartz and chlorite at the transition between prehnite-pumpellyite and lower greenschist facies. Thus, the occurrence of actinolite (together with albite, chlorite and epidote) in mafic intrusives of the Wrangel Complex tends to place these rocks firmly within the lower greenschist facies. For the Phanerozoic succession, the occurrence together of chlorite, muscovite, quartz and albite can be typical of metamorphic conditions prevailing throughout the prehnite-pumpellyite and lower greenschist range. Lacking detailed knowledge of the submicroscopic mineralogy of pelite assemblages, the lower temperature range of Phanerozoic rocks of Wrangel Island remains indeterminate.

Organic geochemical analyses of a Permian argillaceous limestone and a Triassic black slate reveal a Total Organic Carbon content of less that 0.3 per cent (L.R. Snowdon, pers. comm., 1987). Indicated levels of thermal alteration lie far beyond the oil window. Fossil spores and pollen are exceedingly rare in the Phanerozoic pelitic rocks of Wrangel Island. Low preservation is probably due to the brittle nature of these delicate fossils under conditions of high thermal alteration. Alternative indications of thermal maturity have been obtained from Carboniferous and Permian conodonts. Reflected-light conodont colours generally range from light grey to dark grey. Colour Alteration Indices reported by Henderson et al. (1991; Appendix 1) for five collections are 6–6.5 (2), 6.0 (1), 5.5 (1) and 2.5–3.0 (1). The last collection is considered clearly anomalous because it lies one metre above a sample having CAI values of 6.0. The indicated level of thermal maturation lies well beyond the limit of dry gas preservation. Heating experiments under laboratory conditions (Harris and Rejeben, 1986) induced grey alteration colours (CAI = 6.0) in conodonts at 360–550°C.

In the present context, lower greenschist facies metamorphism might be considered as lying in the mineral assemblage range between the first appearance of actinolite in mafic rocks and the first appearance of biotite in psammo-pelitic rocks. The implied temperature envelope for normal pressure conditions lies roughly between 350 and 425° (Winkler, 1979). These temperatures are consistent with those implied by Colour Alteration Indices of conodonts.

In conclusion, the rocks of the Wrangel Complex, although displaying textures consistent with intense deformation and, commonly, pervasive cataclasis, have undergone only lower greenschist facies metamorphism. Overlying rocks of Devonian through Triassic ages are apparently less deformed and generally possess many primary sedimentary textures in spite of a ubiquitous transecting or bedding-parallel cleavage. Nevertheless, metamorphic mineral assemblages in these rocks, considered together with Colour Alteration Indices of conodonts, indicate a metamorphic grade that, like the Wrangel Complex, also lies within the lower greenschist facies. Implied paleotemperatures are in the range of 350 to 425°C for normal pressure conditions during regional metamorphism.

Higher levels of metamorphism, ranging to lower amphibolite grade, have been suggested by Kameneva (1975, 1977) and Kameneva and Il'chenko (1976) for some mineral assemblages of the Wrangel Complex. These observations could not be confirmed with the materials available to us.

## TECTONIC HISTORY

### Introduction

The tectonic history of Wrangel Island can be inferred from depositional environments, composition and fabric of conglomerates, K–Ar and U–Pb isotopic histories, magmatic episodes and deformational history (Fig. 61). These events are presented in chronological order, and are compared with correlative geological events in the circum-Arctic region bordering Canada Basin. The region compared includes the Arctic Alaska–Chukotka Ancestral Plate (Arctic Alaska–Chukotka terrane of Churkin, 1982), and the western Canadian Arctic Islands part of the North American tectonic plate. The Arctic Alaska–Chukotka Ancestral Plate embraces the continental shelves of the East Siberian and Chukchi seas, Wrangel and Herald

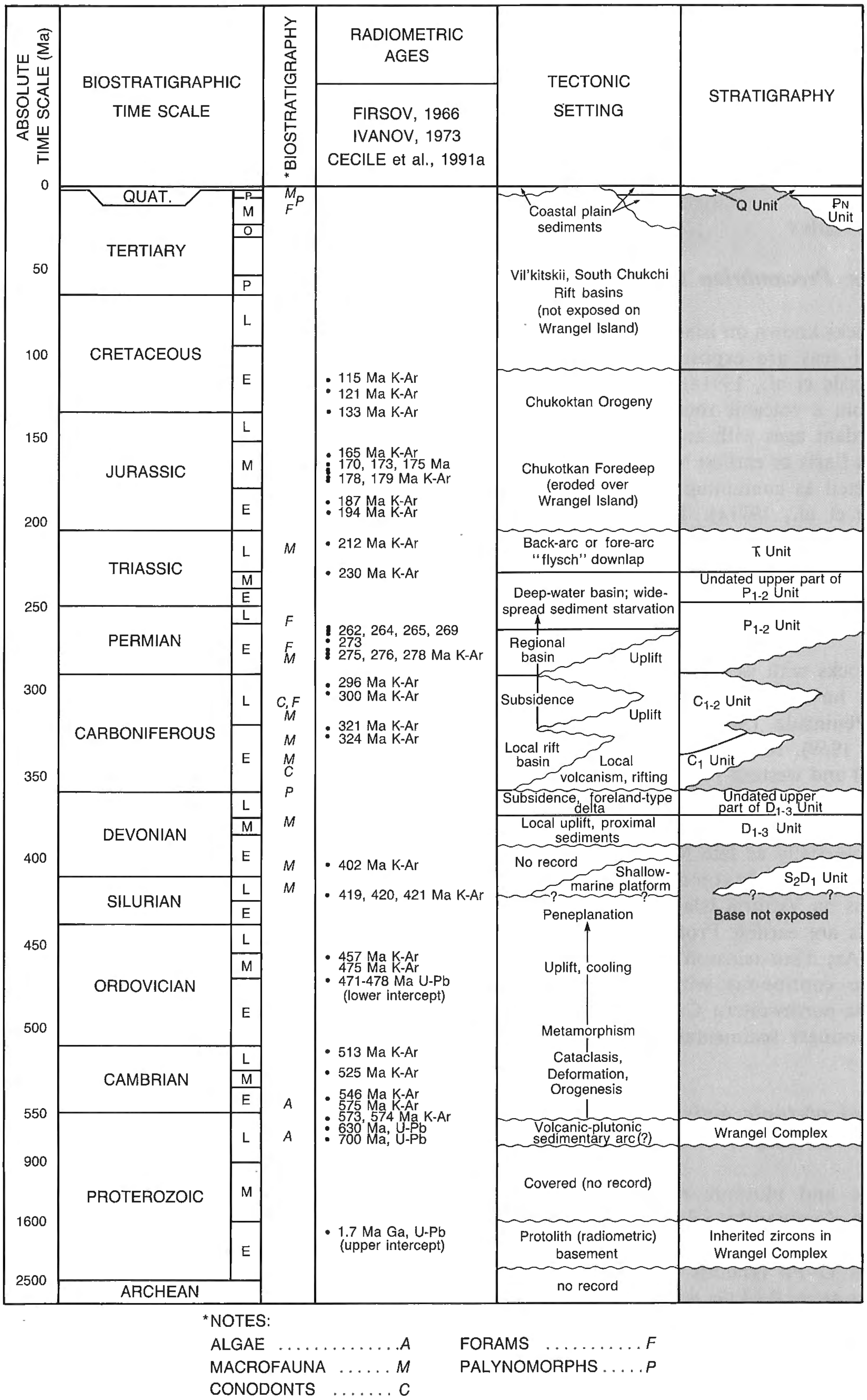


***Figure 61.*** *Tectonic history of Wrangel Island. K–Ar ages are given as published without standardizing decay constants and adjusting ages accordingly.*

islands and the New Siberian Islands, the northern Chukotka Peninsula, and the Brooks Range and North Slope of Alaska. In a few cases, evidence from the periphery of this area, as well as geological events important elsewhere, are cited.

## Wrangel Complex

### *Evidence for Precambrian basement*

The oldest rocks known on islands in the East Siberian and Chukchi seas are exposed within the Wrangel Complex (Cecile et al., 1991a). Two zircon separates recovered from a volcanic rock in this complex gave highly discordant ages with an upper intercept of ca. 1.7 Ga (latest Early or earliest Middle Proterozoic) and were interpreted as containing crystals with inherited cores (Cecile et al., 1991a). The implication is that some Wrangel Complex zircons may have been derived from an underlying early to mid-Precambrian basement terrane of igneous-metamorphic and/or supracrustal character.

Granitic rocks with isotopic ages as old as ~1580 Ma (K-Ar) have been reported from northern Chukotka Peninsula (Shilo and Zagruzina, 1965; Gnibidenko, 1969). Metamorphic and plutonic rocks of the central and western Brooks Range are generally much younger (<.85 Ga). Similarly, basement gneisses of Pearya Terrane of northwest Ellesmere Island are dated radiometrically as late Middle Proterozoic (ca. 1.1 Ga, Trettin, 1987). In contrast, inliers of basement granitic gneiss on Victoria Island in the southwestern Arctic islands are earliest Proterozoic-latest Archean (2.41 Ga K-Ar; Thorsteinsson and Tozer, 1962) and probably are continuous with the Archean Slave Craton of the northwestern Canadian Shield beneath intervening younger sedimentary cover.

### *Volcanic and plutonic activity (~630 to ~700 Ma)*

The volcanic and plutonic rocks of the Wrangel Complex are dominantly acidic to intermediate in composition and likely accumulated in a marine environment. U-Pb igneous ages date one of the volcanic rocks as ca. 0.63 Ga and one of the plutons as ca. 0.7 Ga. These data point to a long-lived igneous-sedimentary event in Late Proterozoic time. These rocks cannot be confidently assigned to any specific tectonic setting with the presently available data. Nevertheless, the rarity of mafic volcanic rocks in the succession and the timing of this activity, immediately prior to a major tectonic event in the latest Proterozoic-early Paleozoic, tends to increase the likelihood of this succession having been part of a continental or oceanic volcanic arc complex.

Shilo and Zagruzina (1965) and Gnibidenko (1969) reported K-Ar ages of 0.76 Ga from a biotite granite gneiss, and 0.72 Ga from mica-quartz slate with granite collected on the northeastern Chukotka Peninsula. A granite of pre-Early Carboniferous age is known from Cape Kiber (Fig. 1), on the northern coast of the Chukotka Peninsula (Cecile et al., 1991b). Kos'ko et al. (1990) have hypothesized a Late Proterozoic age for melanocratic schists and gabbros of southeastern Bol'shoi Lyakov Island in the New Siberian Islands (Fig. 1).

In the western Brooks Range, a recently dated granite has yielded a U-Pb zircon age of 705 Ma (Karl and Aleinikoff, 1990), very close to the ca. 700 Ma age from the granitic sill intruding the Wrangel Complex. K-Ar geochronology on single minerals from quartzose and mafic schists in the Brooks Range have given a variety of Proterozoic ages (Turner et al., 1979). In particular, muscovites from muscovite schists gave ages of 638±25 and 634±25 Ma. All other examples suggest slightly older ages. Karl et al. (1989) determined a 750 Ma U-Pb zircon age for granitoid rocks in a gabbro-granite complex in the western Brooks Range. In the Seward Peninsula, Churkin (1973) reported a 750 Ma Rb-Sr whole rock age for a gneiss. Central Brooks Range orthogneisses have given U-Pb zircon ages of 688 to 855 Ma (Dillon et al., 1980). These ages were determined on zircons with rounded cores and may include an inherited component. Roots and Parrish (1988) reported a U-Pb zircon age of 751 +26/-18 Ma from a rhyolite of Windermere Supergroup equivalent rocks from the Ogilvie Mountains in the northern Yukon Territory.

In contrast, the Late Proterozoic of the Canadian Arctic Islands is represented by the generally unmetamorphosed Natkusiak tholeiitic flood basalt and sills of Victoria Island (722-25 Ma U-Pb; Heaman et al., 1990). These igneous rocks lie at the epicentre of the Franklin Dyke swarm and are thought to represent the preserved portion of a major thermal plume that preceded the latest Proterozoic rifting phase of the Cambrian to Devonian Franklinian Basin (Harrison, 1991). For most areas of the western Arctic Islands, the geological record of the Late Proterozoic is buried beneath thick sedimentary cover of Early Cambrian and younger ages. Where the base of the Cambrian section is exposed above Proterozoic rocks, there is everywhere a depositional and tectonic hiatus spanning the interval between about 720 and 540 Ma.

### *Orogenesis and uplift (~600 to ~420 Ma)*

Evidence from isotopic ages, Paleozoic conglomerates (with previously tectonized clasts), missing stratigraphic successions, and pervasive cataclastic textures, peculiar to the Upper Proterozoic rocks of the Wrangel Complex, document a major orogenic event in the Wrangel Island area during the time interval between the latest Proterozoic and the Early Silurian. Conglomerate at the base of the $D_{1-3}$ Unit contains abundant clasts derived from the underlying Wrangel Complex, in one place these clasts show older tectonic fabric. In the Tsentral'nye Mountains, the entire Early Cambrian through Silurian stratigraphic succession is missing. Some K–Ar ages and one U–Pb upper intercept indicate a major metamorphic and or cooling event during the early Paleozoic.

Of all the conglomerates represented on Wrangel Island, the basal Paleozoic $D_{1-3}$ Unit of the central Mountains contains the most abundant and coarsest clasts, which appear to have been derived from the Wrangel Complex. These clasts are evidence of a prolonged and substantial period of post-Wrangel Complex erosion during the early Paleozoic. With one significant known exception, most $D_{1-3}$ Unit clasts possess a tectonic fabric that is now concordant with the pervasive Mesozoic tectonic fabric common to all rocks of the central uplift. The exception is at a locality in the area of Krustal'nyi Creek on the north slopes of the Tsentral'nye Mountains. Here several large boulders were found in felsenmeer some tens of metres from the exposed contact between the $DC_1$ and $C_{1-2}$ units. These conglomerate boulders contained clasts displaying an older tectonic fabric (Fig. 24). Although the exact bedrock source for these boulders could not be found during the time available, there can be no reasonable doubt of their local origin and probable Devonian or possible Early Carboniferous age. The clasts are angular and scattered through a sparse argillaceous matrix now represented by an assemblage of metamorphic chlorite, muscovite, quartz, and albite. Clast types are dominated by rocks of felsic to intermediate plutonic composition. Cataclastic textures and crosscutting veins in these clasts are clear evidence of a major phase of deformation that must have followed the firmly dated Late Proterozoic plutonic phase in the Wrangel Complex. This deformation must also have preceded uplift, erosion and mid-Paleozoic resedimentation.

Timing of this deformation is constrained by the K–Ar age determinations on Wrangel Complex rocks, made by Firsov (1966; also reported on in Ivanov, 1973). These ages display a wide scatter between 115 and 575 Ma. The oldest ages are 575 and 574 Ma (latest Proterozoic) from a coarse grained granite porphyry, and 513 Ma (Late Cambrian) from a quartz-muscovite-feldspar schist.

Younger K–Ar ages, from leucocratic granites, quartzo-feldspathic schists, granodiorite porphyry, amphibolite and "gneisses" of the Tsentral'nye Mountains form two sets: one clustering between 420 and 457 Ma (Middle Ordovician–Early Silurian), and the other between 115 and 296 Ma (Late Carboniferous–Early Cretaceous). A lower U–Pb intercept on a volcanic rock gave values of 471–478 (Cecile et al., 1991a). The younger dates probably represent late cooling ages and/or the effects of Chukotkan (Mesozoic) orogenesis. The older 575 Ma to 420 Ma ages are interpreted as late metamorphic and final cooling ages associated with uplift after the first major phase of deformation of the Wrangel Complex.

On Henrietta Island of the northern New Siberian Islands, there is a succession of "young" Paleozoic clastic and volcaniclastic strata that are intruded by dykes and sills of intermediate to mafic composition. These plutonic rocks gave K–Ar ages varying from 310 to 450 Ma (Vinogradov and Yavshits, 1975). The uncertainty in the age of the host rock makes the significance of these data difficult to assess.

Within northern Chukotka there is tenuous evidence for a possible early Paleozoic orogenic "event". A granite intrusive of assumed early Paleozoic age ("pre-Lower Carboniferous") outcrops to the east of Pevek (Fig. 1; Kos'ko et al., 1990; Cecile et al., 1991b). In a tabulation of K–Ar dates from northeastern Chukotka, Shilo and Zagruzina (1965) and Gnibidenko (1969) reported the following Early Ordovician through Early Silurian ages: 430 Ma from quartz-biotite slate; 432 Ma from a granite gneiss; and 502 Ma from a granite gneiss. Mesozoic ages are also represented. The Ordovician and Silurian dates could represent metamorphic or cooling events similar to those associated with the Wrangel Complex rocks.

Roughly coeval or somewhat younger deformation and uplift is documented only within the Pearya composite terrane of northwestern Ellesmere Island. Here Trettin (1987) has documented the Middle Ordovician M'Clintock Orogeny, which was accompanied by metamorphism to amphibolite grade and granitic plutonism.

In the rest of the Canadian Arctic Islands, Cambrian and Ordovician strata are extensively preserved in either the continuously subsiding craton-marginal Franklinian shelf or correlative deep water basins (Trettin, 1973, 1992).

In the northern Canadian Cordillera and Alaska, Cambrian and Ordovician rocks are extensively preserved in both thick platform facies and thin basin facies (Churkin, 1973; Lane and Cecile, 1989; Cecile and Norford, in press). There is no substantial evidence in these areas of Cambrian or Ordovician orogenesis.

## Evolution of middle Paleozoic strata

### *Upper Silurian through Early Devonian*

Upper Silurian to Lower Devonian strata represent a period of stability during which mostly shallow-marine sediments accumulated in the Wrangel Island area. The absence of Silurian and Lower Devonian rocks below Devonian strata in the Tsentral'nye Mountains is interpreted as either inheritance of topography following latest Proterozoic–early Paleozoic deformation and uplift, or erosion of rocks of this age during subsequent epeirogenic events in later Devonian time.

Continuous sedimentation on shallow-water carbonate platforms and within flanking deep-water, mudrock/siltstone-filled basins is typical of northern Chukotka (mainland and New Siberian Islands), northern Alaska, northern Yukon and the southern and western Canadian Arctic Islands. In contrast to these areas, very thick and rapidly deposited volcanic arc- and orogen-derived strata, dominated by siliciclastic sediment gravity flows ("flysch"), are representative of Late Silurian and Early Devonian deep-water basins and carbonate shelves of Ellesmere Island. In addition, proximal deposits, featuring terrigenous siliciclastic rocks, are common to some formations of Late Silurian and Early Devonian ages deposited over, and adjacent to, basement-cored uplifts of the southeastern Canadian Arctic Islands (Boothia and Bache Peninsula uplifts), Pearya and northern Wrangel Island (Churkin, 1973; Bondarev et al., 1973; Sosunov et al., 1982; Krasnyi and Putintsev, 1984; Trettin, 1973, 1987, 1992; Kos'ko et al., 1990).

### *Devonian*

Devonian strata of Wrangel Island are interpreted as marginal marine followed by deeper water clastic facies recording submergence of the Upper Silurian–Lower Devonian stable shelf. Initially, a major topographic high existed in the Tsentral'nye Mountains. Sediment dispersal from this high resulted in a fringing conglomeratic facies of Devonian age preserved at the base in $D_{1-3}$ Unit strata. The uplift was subsequently buried by younger Devonian, far-travelled, finer grained sandstone, slate and argillite.

Devonian strata of northern Chukotka Peninsula are similar in facies and composition to the Devonian sandstone and slate strata of Wrangel island (Kos'ko et al., 1990; Cecile et al., 1991b). On the New Siberian Islands, and on the northeast tip of Chukotka, Devonian strata are a mixture of clastic rocks and carbonate (Rogozov and Vasil'eva, 1968; Oradovskaya, 1971, Oradovskaya and Obut, 1977; Kos'ko et al., 1990).

The history of Wrangel Island Devonian sedimentation is very similar to that known in parts of the Canadian Arctic Islands. In the western Arctic Islands, carbonate buildups and deeper water mudrocks of Early Devonian age are subsequently buried by Eifelian and younger Devonian progradational clastic rocks associated with sedimentation in the foreland of the Ellesmerian orogen. The basement-cored uplifts of the central and eastern Arctic Islands, each fringed by proximal clastic wedges, are similarly buried by the Ellesmerian foreland basin succession. Pearya Terrane is recognized as part of a probable source area for these thick and widespread deltaic deposits (Embry, 1988; Trettin, 1987, 1992). Orogen-derived clastic rocks are also typical of the Frasnian and Famennian interval in the northern Yukon and of the Endicott Group in the northern Brooks Range (Gordey et al., 1982, 1987; Oldow et al., 1987; Gordey, 1988; Moore et al., 1989), a succession that may be continuous with the Devonian siliciclastic rocks of Chukotka and Wrangel Island.

## Upper Paleozoic tectonics

### *Lower Carboniferous (Tournaisian-Viséan)*

Lower Carboniferous strata on Wrangel Island represent a variety of facies and are of variable thickness. Most notable is a locally restricted facies of thick intraclast polymictic conglomerate, arkosic sandstone and lesser evaporite. The composition, immaturity, local provenance, and variable thickness of the conglomerate of this facies is consistent with a syntectonic setting featuring local uplifts and depressions, and relief associated with sedimentation in basins or channel systems of limited extent. A rift-related setting is suggested. In the north, basic and acidic volcanic rocks, hypothesized as correlative with the Lower Carboniferous succession, could also be the products of extensional tectonism and would corroborate the rift interpretation.

The association of conglomerate with rocks of Carboniferous age is typical of many land areas in the East Siberian Sea and the adjoining mainland (Sosunov et al., 1982; Kos'ko et al., 1990). On Henrietta Island, in the New Siberian Islands, there are clasts of granite, gneiss and micropegmatites in a succession of tuffaceous gritstone and sandstone in the upper part of a "young" Paleozoic succession (Vinogradov and Yavshits, 1975). In northern Chukotka similar depositional facies are present. Lower Carboniferous limestones, with locally derived, coarse, sedimentary-clast conglomerate are known from at least two locations on the mainland south of Wrangel Island (Cecile et al., 1991b). In one of these occurrences (Cape Kiber area, Fig. 1) there are a significant number of granitic clasts interpreted as being from a local pre-Carboniferous granitic intrusive exposed in the area (Cecile et al., 1991b).

The northern Yukon and Brooks Range of northern Alaska record either semicontinuous deposition of proximal facies sandstone and conglomerate across the Famennian–Tournaisian boundary in the upper Endicott Group, or a hiatus and regional unconformity beneath Lower Carboniferous basal conglomerate of the Kekiktuk Formation (Oldow et al., 1987; Gordey, 1988; Moore et al., 1989).

Rocks of latest Devonian, Tournaisian and early and middle Viséan ages are missing from the Canadian Arctic Islands. This was a period of high topographic relief following the Arctic Islands-wide Ellesmerian Orogeny (Trettin and Balkwill, 1979; Trettin, 1992).

In the northern Canadian Cordillera this period of time is more enigmatic and complex, and is associated with large areas that have undergone uplift and extensional tectonism. Upper Devonian through Lower Carboniferous strata include channels and/or local basins filled with sedimentary-clast conglomerate, mostly chert and clasts from older lower Paleozoic and Proterozoic strata (Gordey et al., 1982; Gordey et al., 1987; Gordey, 1988).

### *Lower and Upper Carboniferous*

$C_{1-2}$ Unit strata of Wrangel Island represent a return to more stable conditions in the Carboniferous. An extensive carbonate platform was established in the Viséan. The platform expanded to the northwest through the Moscovian. There was a parallel expansion of a deeper marine facies from the southeast as demonstrated by fining- and deepening-upward sedimentary trends in the Carboniferous succession of the Tsentral'nye Mountains.

Similar carbonate successions of approximately the same age are found throughout northern Chukotka (Sosunov et al., 1982; Krasnyi, and Putintsev, 1984; Kos'ko et al., 1990).

Regional expansion of shelf carbonate and basin facies rocks is also typical of the middle Carboniferous Lisburne Group in northern Alaska and northern Yukon (Bamber and Mamet, 1978; Armstrong and Mamet, 1985). Regional variations in depositional facies document the progressive drowning of an exposed mid-Paleozoic landmass that once existed in the north and northeast.

In the Canadian Arctic Islands, rift-related sedimentation began in the late Viséan and was associated with thermal collapse and extension over the site of the pre-existing Franklinian Mobile Belt (Ellesmerian orogen). Rifting continued through the Carboniferous with important rift-axial redbeds and evaporites of Namurian–Bashkirian ages. Expansion of this ancestral Sverdrup Basin rift system to the southeast, southwest and northwest led to rift marginal redbeds of Bashkirian and Moscovian ages and coeval, rift axial, deep-marine mudrocks and flanking carbonate platforms (Beauchamp et al., 1989a, b; Trettin, 1992). Alkalic basalt is associated with Sverdrup Basin rifting in the northwestern Arctic Islands, where two distinct volcanic episodes have been identified: the first in the Namurian and the second in the Late Carboniferous (Trettin, 1988; Cameron, 1989).

### *Permian*

Permian rocks on Wrangel Island document a continuation of the shallow-water carbonate deposition to the northwest and coeval basinal conditions to the southeast. In the north and west, however, the base of the Permian is marked by a disconformity. Basal strata in these areas include either polymictic pebble conglomerate or olistostromes and polymict breccia. The Permian breccia along the lower Neizvestnaya River includes clasts of Silurian carbonate. The Permian beds also overstep Carboniferous and Devonian rocks and are locally found to rest directly on the Silurian. A renewed phase of uplift is indicated, possibly marking a late stage of rift-related extension in the Wrangel island area.

In the southern half of the island, limestone, typical of the middle $P_{1-2}$ Unit, gives way upward to fairly uniform, black marine slate in the younger Permian strata. In Late Permian time, northern Wrangel Island was a shallow-water area and southern Wrangel Island was in basinal facies. By latest Permian the entire island may have been deeply submerged and sediment starved.

A thin (200 m) slate–argillite-dominated Permian succession is known on Kotel'nyi Island, New Siberian Islands (Vol'nov et al., 1974; Kos'ko et al., 1990). On nearby Bol'shoi Lyakov Island, the Burustas Suite, which is about 1200 m thick and consists mainly of interstratified sandstone and argillaceous rocks, yielded Permian miospores from its lower half (Vinogradov et al., 1974).

In the eastern part of northern Chukotka, an undivided succession of sandy and coaly shales is assumed to be Late Carboniferous and Early Permian in age. These strata are overlain by coaly shale, siltstone and sandstone assumed to be Late Permian (Kos'ko et al., 1990). An undivided basin facies slate succession of assumed Permian and Triassic age is found in the Chaun zone of the Pevek area (Fig. 1) on northwestern northern Chukotka (Kos'ko et al., 1990).

In northern Alaska, the Permian section is represented by thin, shallow-marine deposits in the north, and thin, deeper water deposits in the south (Detterman et al., 1975). In the northeastern part of Alaska, basal Permian deposits rest unconformably on Carboniferous limestone and feature conglomerate-filled channels (Crowder, 1990), a situation similar to that observed across parts of northern Wrangel Island.

The Permian in the Canadian Arctic Islands is distributed in roughly annular facies belts around the Sverdrup Basin. Starved basin facies strata typical of the basin centre are overlain, without apparent break, by marine Lower Triassic strata. Toward the basin margin, Carboniferous limestone is continuous into the Permian. On the basin edge, the Permian (a mixed assemblage of sandstone, mudrock and limestone) oversteps the Carboniferous and is locally documented to rest directly on rocks as old as the Ordovician. Tectonism and alkali basalt volcanism is associated with the Melvillian Disturbance, a phase of basin-marginal transpressive rift-inversion that produced local fringing clastic wedges and chert pebble conglomerate in the Artinskian (Beauchamp et al., 1989a; Harrison, 1991).

## Chukotkan Foredeep and Orogeny

### *Triassic flysch*

The authors of this report remain divided over the origin and tectonic significance of the sub-Triassic surface in the Mineeva Mountains (see earlier discussions in sections on Triassic and Structure). In this area, deep-marine siliciclastic sediment gravity flows (flysch) typical of the Triassic are observed to rest variably on $P_{1-2}$ Unit slate, and $C_{1-2}$ Unit limestone and sandstone. If an unconformity exists, it implies exposure of parts of the upper Paleozoic prior to flysch sedimentation; if the surface is structural, no exposure is required.

Strata of latest Permian, and Early and Middle Triassic ages are not documented with certainty on Wrangel Island. It is possible, however, that this time interval is represented within a widespread, basin facies, black slate preserved around the transitional boundary between $P_{1-2}$ and Tr unit strata on the west and east ends of the island, where a complete stratigraphic record may exist without structural and/or erosional truncation.

The remainder of the Tr succession, assumed to be mainly Upper Triassic, is a progradational assemblage of compositionally immature siliciclastic sediment gravity flows (flysch) derived from nearby uplands.

The nature of these uplands is somewhat enigmatic. The flysch deposits appear to be too early for Chukotkan orogenesis, which is thought to have been most active between Middle Jurassic and Early Cretaceous time. They may instead be the products of uplifts accompanying local volcanism.

Wrangel Island Triassic strata can be genetically linked to the Russian mainland. There, similar, deep-marine, siliciclastic flysch deposits are typical of the Late Triassic throughout the northern Chukotkan Peninsula (north of the South Anyui Suture). These flysch deposits are interstratified with limited volumes of volcanic rocks (Yu.M. Bychkov, pers. comm., 1988; Bychkov, 1991). In some sections spilitic basalt makes up 15 per cent of the succession (Velmai Uplift) and volcaniclastic rocks and andesitic tuffs have also been observed (Yu.M. Bychkov, pers. comm., 1988; Bychkov, 1991).

On Kotel'nyi Island in the New Siberian Islands, Upper Triassic strata consist of just under 1000 m of fossiliferous argillite and shale with minor limestone and sandstone (Preobrazhenskaya et al., 1975).

In the Alaskan Chukchi Sea area, the Upper Triassic is continuous with older Triassic and Permian rocks in a relatively thin succession of marine sandstone, calcareous siltstone, shale, limestone, and calcareous, variably phosphatic mudstone (Thurston and Theiss, 1987). Over most of northern mainland Alaska the Late Triassic is represented by a fossiliferous, condensed succession of dark coloured calcareous shale, siltstone, limestone and chert (Detterman, 1973; Detterman et al., 1975). Triassic flysch deposits have been reported from the Lisburne Peninsula area (C.S. Cameron, pers. comm., 1987; I.L. Tailleur, pers. comm., 1988). In northeastern Alaska, Triassic strata comprise a thin succession of deltaic or shallow-water siltstone, sandstone and mudrock (Crowder, 1990). In the northern Yukon only a discontinuous thin upper Triassic is present and consists of mixed carbonate and clastic facies.

In the Canadian Arctic Islands, Triassic strata were deposited in basin-axial and basin-marginal belts of the Sverdrup Basin (Embry, 1992). In the late Early Triassic, most of the west-central Canadian Arctic Islands covered by deep-marine mudrock, and in the northwest, southwest and south by shallow-marine and nonmarine clastic rocks. By latest Triassic, deltaic deposits of the Heiberg Group, originating from continental North America, occurred throughout all but a portion of the southwest where marine mudrocks were predominant.

### *Mesozoic orogenesis*

Northern Chukotka has been divided into two major fold belts: the Chukchi fold belt, which includes the mainland, Wrangel Island, and associated Chukchi Sea continental shelf, and the New Siberian fold belt, which includes the New Siberian Islands and surrounding East Siberian Sea continental shelf east and west of the islands (Gramberg et al., 1986). These two fold belts, as well as the Verkhoyansk fold belt, which is juxtaposed with the west end of the New Siberian fold belt, and several smaller fold belts surrounding Pacific-side terranes of southern Chukotka (including the South Anyui), underwent intense pervasive deformation and were intruded by granitic plutons during the Middle Jurassic to Lower Cretaceous Chukotkan Orogeny. The time of initiation and completion of intense deformation varies slightly across the area. In general, the onset of the most intense deformation is Middle Jurassic (K.V. Paraketsov, pers. comm., 1989). The overlap of the relatively undeformed, epicontinental Okhotsk-Chukotsk volcanic belt across all of these terranes, including northern Chukotka, provides an upper age limit of late Early Cretaceous (Rozenbloom et al., 1987; Cecile et al., 1991b). The age of deformation of the Oloi–South Anyui fold belts, which are hypothesized to stitch southern Pacific-side terranes to northern Chukotka, is late Middle Jurassic to Early Cretaceous (C.V. Paraketsov, pers. comm., 1989).

In the Wrangel Island area, Chukotkan deformation was achieved during a four-stage, continuous, compressional event that involved a strong component of thin-skinned, horizontal shortening and a minor component of right-lateral slip.

Structural trends over most of mainland northern Chukotka are generally northwesterly with northeast vergence. The associated rocks are intensely and penetratively deformed, with tight and overturned folds and thrust faults (Rozenbloom et al., 1987; Cecile et al., 1991b). The trend of these structures is slightly oblique to the sublatitudinal orientation of folds and thrusts exposed on Wrangel Island. One important exception within the Arctic Chukotkan plate, of unknown significance, is the Kolyuchin Zone (Fig. 8), a north-trending Mesozoic fold belt that obliquely traverses the eastern end of the Chukchi fold belt. In addition, the northwest-trending New Siberian fold belt, intensely deformed during Mesozoic orogenesis, is considered by Gramberg et al. (1986) as a separate structural domain.

The Brooks Range of northern Alaska was created during a stage of prolonged Mesozoic compressive deformation during the Middle Jurassic through Early Cretaceous (Brookian Orogeny). Mayfield et al. (1983) reported that the oldest sedimentary record of this event is Middle Jurassic (Bajocian), and the oldest undeformed rocks are Lower Cretaceous (Albian). In the central Brooks Range, Mull et al. (1987) showed that the youngest rocks involved in major Brooks Range structures were Early Cretaceous in age. Norris (1973) dated the major period of Mesozoic deformation in the northern Yukon as late Early Jurassic to late Lower Cretaceous. In the northern Yukon, rocks of Late Cretaceous age and younger, although themselves moderately deformed, overlap major structures represented within Lower Cretaceous and older rocks (Norris, 1974; Norris, 1985). Thus, northern Chukotka, northern Alaska and the northern Yukon have all experienced an intense period of deformation that began sometime between latest Early and Middle Jurassic time, and was largely completed by late Early Cretaceous.

There is no equivalent orogenic episode in the Canadian Arctic Islands. The Sverdrup Basin remained the locus of relatively passive and waning subsidence throughout the Triassic, Jurassic and Early Cretaceous, with a limited sediment influx from all sides (Balkwill and Fox, 1982; Stephenson et al., 1987; Embry, 1992). Smaller sedimentary basins lying near and parallel or somewhat oblique to the present margin of the Arctic continental shelf but outside the Sverdrup Basin depocentre record a renewed phase of rifting and syntectonic sedimentation during the interval between the Middle Jurassic and the Early Cretaceous (Harrison et al., 1988).

### *Formation of peripheral basins*

Following Chukotkan deformation, large extensional basins formed north, south, east and west of Wrangel Island. Sedimentary detritus was eroded from Wrangel Island (Wrangel-Herald Arch) and Chukotka and deposited into these basins (Fig. 5; Kos'ko, 1984; Pol'kin, 1984; Grantz et al., 1990). These basins are only known seismically (see Regional geological setting) and are thought to be filled with as much as 4 km of upper Lower Cretaceous through Quaternary strata (Figs. 7a, b). Grantz et al. (1990) interpreted the lower two thirds of the stratigraphic succession in the North Chukchi/Vil'kitskii Basin as having undergone extensional deformation sometime during the Cretaceous. The South Chukchi (Hope) Basin contains a similar seismic stratigraphy, but is essentially intermontane and overlies Chukotkan-Brookian deformed basement. The North Chukchi has a complex basement of varying ages, but it includes relatively undeformed upper Paleozoic and lower Mesozoic strata that predate Chukotkan-Brookian deformation. The western North Chukchi and associated Vil'kitskii basins appear to be shelf-margin features overlying attenuated or transitional crust.

These geophysically documented basins of the continental shelf are correlative with clastic basins found in the Beaufort-Mackenzie Basin, northern Yukon and western and northern Alaska. The North Chukchi and Vil'kitskii basins are likely very similar to Alaskan North Slope and Beaufort-Mackenzie basins (Dixon et al. 1985; Grantz et al., 1990) but likely with their own distinctive source areas for clastic material. The South Chukchi and East Siberian Sea basins are similar in tectonic setting to the Colville Foredeep, mainland northern Yukon and to the postorogenic Albian and younger phase of the Yukon-Koyakuk Basin of western Alaska.

In the western Canadian Arctic Islands, the Sverdrup Basin and the smaller peripheral basins lying along the continental margin continued to develop and to receive appreciable siliciclastic detritus throughout the late Early and Late Cretaceous. Basalt flows and feeder gabbro sheets and dykes are also found within strata of this age, especially on Axel Heiberg and northwestern Ellesmere islands. The flows, dated along with the enclosing strata, are related to four episodes that occurred between the Barremian and the Maastrichtian (Embry and Osadetz, 1988).

Similar mafic sills are found in Cretaceous strata exposed on the New Siberian Islands (Kos'ko et al., 1990). These exposures are also associated with basalt and basaltic tuff of Bennett Island and mafic dykes intruding a variety of older strata on the large central New Siberian Islands. On Bol'shoi Lyakov Island, in the south of the chain, granitic sills give K-Ar ages of 95-110 Ma (Kos'ko et al., 1990).

### *Tertiary tectonics*

Orogenic activity in the Canadian Arctic Islands (Eurekan Orogeny) is entirely younger (Maastrichtian through Eocene-Oligocene; De Paor et al., 1989) than activity in the Wrangel Island and western Alaska-Chukotka region, and is related to the collision of Greenland and Ellesmere Island (Trettin and Balkwill, 1979). Nevertheless, geological and geophysical evidence from the eastern North Slope and Brooks Range region of Alaska, northern Yukon and the offshore Beaufort Sea area points to the existence, in these areas, of an Eocene to Miocene contractional orogen that prograded across the Late Cretaceous-Tertiary continental margin (Dixon et al., 1985; Grantz et al., 1987; Dietrich and Lane, in press).

There is no obvious evidence of Tertiary shortening in the Wrangel Island, Chukchi Sea, and East Siberian Sea areas. This region appears to have been in a state of continuous subsidence and extension through the Miocene and Pliocene(?). Young olivine basalt flows exposed on Zhokov and Vil'kitskii islands, New Siberian Islands, are considered part of this tectonic regime. K-Ar ages of 3-10 Ma have been obtained from these rocks. However, paleomagnetic data suggest they may be as old as 10-20 Ma (Kos'ko et al., 1990).

### *Significance of the Chukchi syntaxis*

There are numerous similarities between the Alaskan and the Chukotkan parts of the Alaska-Chukotka Ancestral Plate. However, the front of penetrative Brookian-Chukotkan deformation is offset or deflected to the northwest by 600+ km in the Chukchi Sea area (Fig. 5, the Chukchi syntaxis of Tailleur and Brosgé, 1970).

The front of Brookian deformation can be traced westward in Alaska to the southern Lisburne Peninsula. The front here turns northwest and follows along the northern edge of the Wrangel-Herald Arch. Conventionally the front (now Chukotkan) then turns back to the west, just north of Wrangel Island (see Kos'ko et al., 1990; Grantz et al., 1990). However, the present report demonstrates that rocks on northern Wrangel Island are so intensely deformed that it is unlikely that the front of Chukotkan deformation is immediately offshore of Wrangel Island as was previously assumed (e.g., Grantz et al., 1990), but instead lies much farther north, possibly at the edge of the Russian Arctic continental shelf.

The nature of this offset or deflection in the orogenic front is not understood. Published seismic lines that cross the northwest-trending part of this feature (Thurston and Theiss, 1987) show both abrupt and transitional contacts that do not allow an unequivocal interpretation. This feature could be simply a right-angle bend along the eastern limit of an orogenic salient beneath the East Siberian Sea (A.G. Grantz, pers. comm., 1990). Alternatively, the offset in the deformation front may be the expression of a major right-lateral offset between separated links on the orogen. The pattern of tectonic strain and the thin-skinned kinematic model for the Chukotkan deformation within Wrangel Island's central uplift is consistent with this second interpretation.

## DISCUSSION OF TECTONIC HISTORY

One the fundamental benefits of understanding the tectonic history of Wrangel Island in a circum-Canada Basin context is the constraints this history places on Arctic Ocean plate reconstructions. There are numerous models for the origin of Canada Basin, most of which are constrained by only general regional observations. These models are extensively reviewed by Lawver and Scotese (1990). The most popular western model involves the opening of Canada Basin by counterclockwise rotation of the Arctic Alaska-Chukotka Ancestral Plate (Arctic Alaska-Chukotka terrane of Churkin, 1982) away from Arctic Canada about a pivot point situated in the northern Yukon (Carey, 1958; Hamilton, 1970; Tailleur, 1973; Embry, 1990). The most popular model in the former Soviet Union involves the formation of the Arctic Ocean by oceanization of continental crust, first proposed by Shatsky (1935), later modified to one of lithospheric oceanization and granitization (Pogrebitsky et al., 1984). Lawver and Scotese (1990) cited a variety of models, most of which fall under the following categories: entrapment of older oceanic crust, rotation, "in-situ" sea floor spreading, movement of continental blocks by strike-slip, and a combination of strike-slip and oceanic entrapment.

Despite the current popularity of the rotation model in the west and of the oceanization model in the former USSR, none have been rigorously tested by detailed geological observations around the circum-polar rim. Moreover, we do not have adequate geophysical and geological data defining the basic characteristics of Canada Basin ocean floor. Thus none of these models, and many variations that are based on them, can be totally accepted or rejected.

It is beyond the scope of this manuscript to address in detail all the implications of these data for the various competing circum-Arctic plate tectonic models. However, several aspects of Wrangel Island's tectonic history are peculiar to the island or the Arctic Alaska-Chukotka Ancestral Plate and should be given special consideration in any plate tectonic model. There are also peculiar elements of circum-Arctic geology not found on Wrangel Island or adjacent islands and mainland. The more important of these peculiarities are briefly discussed below.

Upper Proterozoic rocks are known from Wrangel Island, parts of the southern Brooks Range and are also suspected from exposures on the New Siberian Islands, and the mainland. Deformation and uplift of this assemblage sometime between the latest Proterozoic and Early Silurian is established for Wrangel Island. The closest potentially related deformation might be the Caledonian tectonics of the M'Clintock Orogeny in the Early to Middle Ordovician of northern Ellesmere Island.

There are no specific pre-Carboniferous structures comparable or specifically attributable to the widely represented Ellesmerian Orogeny of the Arctic Islands on Wrangel Island, adjacent islands or on the mainland. There is depositional evidence of localized uplifts in the Wrangel island area in the Early Devonian not unlike the basement-involved uplifts of the central and eastern Arctic Islands. There are also foreland basin-type deltaic siliciclastic rocks in the Upper Devonian of Wrangel Island that are not unlike those of the Endicott Group of northern Alaska, where Ellesmerian deformation is documented.

The Late Triassic geology of Wrangel Island documents deep-water flysch sedimentation, a facies that may be linked to flysch deposition associated with volcanism and local uplifts on mainland Chukotka. Flysch deposition is peculiar to this part of the Russian Arctic, and the extreme western Brooks Range.

The Arctic Alaska-Chukotka Plate underwent Brookian–Chukotkan orogenesis during the period of time in which the Sverdrup extensional basin in the Canadian Arctic Islands was very active. This orogenesis and assembly of all Pacific-side terranes was completed by late Lower Cretaceous and all were overlapped by the Okhotsk–Chukotsk epicontinental volcanic belt (see also Rowley and Lottes, 1988).

## SUMMARY

Wrangel Island lies 140 km north of mainland Chukotka and is situated at the juncture of the East Siberian and Chukchi seas. It represents a unique exposure of Precambrian to Quaternary geology on the 700 km wide Arctic continental shelf of northeastern Russia. The island is divided into a northern plain with low-lying hills, a south-central mountain belt, and a narrow southern coastal plain.

The oldest stratigraphic unit is the Upper Proterozoic Wrangel Complex, which outcrops only in the core of the south-central mountain belt. The Wrangel Complex consists of a more than 2000 m of felsic to intermediate volcanic rocks, volcaniclastic rocks, sericitic and chloritic slate/phyllite with minor grey and black slate, quartzite, conglomerate and very minor mafic volcanic rocks. Wrangel Complex sedimentary rocks were deposited in a subaqueous, probably marine setting, but the tectonic significance of the volcanic rocks is uncertain. Wrangel Complex rocks are intruded by quartz–feldspar porphyry, gabbro, diabase, and aplitic felsic dykes and sills and small elongate granitic and aplitic intrusive bodies. U–Pb zircon dating of samples collected from Wrangel Complex igneous rocks has provided crystallization ages of 633 +21/-12 Ma on a volcanic or sub-volcanic rock, 699 ±2 Ma on a porphyritic granite sill, and a very imprecise age of ca. 0.7 Ga on a small leuco-granite.

The oldest known Paleozoic unit on Wrangel Island is a succession consisting of approximately 700 m of Upper Silurian and Lower Devonian fossiliferous quartzose sandstone, siltstone, slate and carbonate ($S_2D_1$ Unit). The $S_2D_1$ Unit, only known in the northwestern and western parts of the island, is interpreted as shallow-marine in origin. These strata are overlain by a Devonian succession consisting of up to 1200 m of marginal-marine and basin-fill clastic rocks, including sandstone, argillite, slate and conglomerate ($D_{1-3}$ Unit). The $D_{1-3}$ Unit is interpreted as initially marginal marine around a central Wrangel Island high, followed by a relatively deep-marine succession. In the south of the island, the $D_{1-3}$ Unit directly overlies the Proterozoic Wrangel Complex. In the central mountains the $D_{1-3}$ Unit is overlain by a Lower Carboniferous succession consisting of up to 350 m of clastic rocks, including sedimentary-clast conglomerate, slate, argillite, and carbonate and gypsum ($C_1$ Unit). The $C_1$ unit is thought to be interstratified with occurrences of basic and acidic volcanic strata found in small areas in the north-central part of the island. The $C_1$ Unit is interpreted as the product of mixed marine and nonmarine environments associated with local rift-related uplift and coeval erosion. Over much of the island, the $D_{1-3}$ and $C_1$ units could not be subdivided and are mapped together as the $DC_1$ Unit. The next youngest Paleozoic unit, overlying the $DC_1$ or $C_1$ units, is a Carboniferous succession up to 1400 m thick ($C_{1-2}$ Unit). Two facies are present: microcrystalline and crinoidal biocalcarenite, fine grained, thin-bedded limestone, and minor slate and argillite, representing a shallow-marine setting, found mainly in the northwest; and limestone interstratified with slate and argillite representing transitional-to-basin setting, found mainly in the southeast. The $C_{1-2}$ Unit is overlain, over most of the island, by a Permian succession of up to 750 m of slate and limestone with minor sandstone, coarse clastic rocks and siliceous strata ($P_{1-2}$ Unit). The Permian succession contains several facies. In the Early Permian, a land area lay to the north, where olistostrome-breccia deposits occur, and shale facies lay to the south; but in the Late Permian, a carbonate platform could be found in the northwest, transitional to basin shale and chert in the far southeast. In the southern part of the central mountains area, the $P_{1-2}$ and the $C_{1-2}$ units are missing beneath Triassic strata. On the north-central part of the island, $P_{1-2}$ strata erosionally overstep, from south to north, the $C_{1-2}$, $DC_1$ and $S_2D_1$ units. The next youngest rock unit on Wrangel Island consists of an 800 to 1500 m thick monotonous succession of Triassic age consisting of interstratified units of repetitive, black, turbiditic sandstone and slate (Tr Unit). This unit is interpreted as a flysch succession derived from local uplifts associated with volcanism south and/or southeast of Wrangel Island.

All rocks of Proterozoic to Triassic age on Wrangel Island have been extensively deformed and metamorphosed to greenschist facies by the Middle Jurassic–Lower Cretaceous Chukotkan Orogeny. They display pervasive south-dipping cleavage and north-verging folds, and are cut by map-scale thrusts, normal faults and strike-slip faults. Contrary to previous interpretations, the general intensity of Chukotkan deformation is high on all parts of Wrangel Island.

Nearly all Chukotkan structures on Wrangel Island can be accounted for by a four-stage, thin-skinned tectonic model. There are multiple detachments throughout the deformed succession but the major ones are in Wrangel Complex slate, Devonian slate and Permian slate. Shortening appears to be at a maximum in the island centre and decreases both east and west.

Following Chukotkan orogenesis, large depositional basins formed on the continental shelf around Wrangel Island. The Wrangel–Herald Arch was a positive feature at this time. However, only a few metres of relatively undeformed Paleogene and Neogene clay and gravel deposits are exposed in the northern parts of the island. The youngest stratigraphic unit on the island is a few metres of indurated Pliocene muds and gravel, and above this are unconsolidated Quaternary clastic sediments.

The tectonic history of Wrangel Island is inferred from depositional environments, composition of clastic strata, isotopic history and deformation history. Isotopic evidence indicates that Wrangel Island is underlain by Precambrian sialic basement. The oldest known tectonic event is Late Proterozoic volcanism and plutonism recorded by the Wrangel Complex. Indirect evidence indicates that this was followed by an early Paleozoic orogenic event culminating with substantial uplift and cooling. The $S_2D_1$ Unit indicates establishment of a stable miogeoclinal facies. In the Devonian a marginal marine facies was established around a remnant central high, which continued to exist following deposition of the $S_2D_1$ Unit. This facies was soon succeeded by a change to submarine conditions represented by remaining clastic rocks of the $D_{1-3}$ Unit. Extensional tectonism is inferred for Early Carboniferous time based on the variety of facies, including local evaporites, and the presence of thick sedimentary-clast conglomerate in the $C_1$ Unit. Stable shelf conditions were re-established during the Carboniferous, and by the middle Carboniferous, small reef complexes developed across the northwest part of the island. By Permian time, however, the northern part of the island was uplifted and eroded during a period of renewed rifting. By the Late Permian, the northwestern island was a carbonate platform transitional to basin shale and chert on the southeast. Accepting the sub-Triassic erosion hypothesis of MPC and MKK, sometime between the latest Permian and Upper Triassic, latest Paleozoic rocks were exposed and eroded in the south-centre island area, and then the entire island area subsided. By the Late Triassic, flysch was being deposited on Wrangel Island and the adjacent mainland. Volcanic strata interstratified with the flysch on the mainland suggest that tectonic activity associated with volcanism may have produced the source areas for the flysch. The entire Wrangel Island area was penetratively deformed and metamorphosed during the Middle Jurassic–Early Cretaceous Chukotkan Orogeny, and subsequently uplifted and deeply eroded. The Chukotkan Orogeny, and the amalgamation of Arctic and Pacific-side terranes was complete before the formation of the overlapping Okhotsk–Chukotsk volcanic belt, which is late Early Cretaceous at its base. In Early Cretaceous time, large extensional basins formed in the continental shelf area around Wrangel Island and received thick accumulations of Cretaceous to Tertiary strata, including basalt along with intrusion of sills. Geophysical data show the Wrangel–Herald Arch as positive source of sediment in the Cretaceous. There is also limited evidence for Tertiary extensional tectonism.

There are many similarities between northern Chukotka–Wrangel Island and northern Alaska. However, the front of intense Brookian deformation in Alaska, in the border area between Alaska and Chukotka, is abruptly right-laterally offset or deflected northward at least to a position north of Wrangel Island and probably as far north as the edge of the Russian continental shelf, a distance of about 600 km. This feature was described as the Chukchi syntaxis by Tailleur and Brosgé (1970). Available geophysical data are equivocal and permit interpretation of this offset as either the result of a swing in the deformation front, and/or strike-slip offset.

Several aspects of Wrangel Island's tectonic history are unique or restricted to the Arctic Alaska–Chukotka Ancestral Plate. Conversely, there are peculiar elements of circum-Arctic geology not found on Wrangel Island or the adjacent islands and mainland. These aspects must be considered as important constraints in Arctic plate reconstructions. Restricted to the Arctic Alaska–Chukotka Ancestral Plate are: Late Proterozoic volcanism and plutonism; hypothesized latest Proterozoic–Early Paleozoic orogenesis and/or uplift; deposition of proximal Triassic flysch with a volcanic association; and intense Middle Jurassic–Early Cretaceous deformation, the front of which is well north of Wrangel Island. Because all terranes, Arctic and Pacific, are overlapped by the epicontinental Okhotsk–Chukotsk volcanic belt, they had to have amalgamated before late Early Cretaceous, during the middle Jurassic–Early Cretaceous Orogeny.

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# APPENDIX 1

## Paleontology

### Wrangel Complex (Upper Proterozoic)

**Pr–F1.** From the southern slopes of the Mamontovye Mountains, at approximately lat. 71°06′N and long. 180°00′E, Kameneva (1975) and Kameneva and Chernyak (1973) reported that recrystallized limestone yielded the microphytolites *Glebosites* sp. cf. *G. glebosites* Reitlinger, which indicates a middle Riphean (mid-Late Proterozoic) age (identified and dated by L.N. Ilchenko and V.E. Mil'shtein). In addition, Kameneva (1975) and Kameneva and Chernyak (1973) reported that the algae *Nubecularites continuus* Mil'shtein, *N. minutus* Mil'shtein, *N. multifarius* Mil'shtein and *Renalcis* Vologdin were recovered (identified and dated by V.E. Mil'shtein) from rocks which we think may be Wrangel Complex. The latter indicate an Early Cambrian age.

### $S_2D_1$ (Upper Silurian–Lower Devonian) Unit

**$S_2D_1$–F1.** Locality 1 (Fig. 2), lat. 71°06′N, long. 179°18′E. From exposures in the middle part of the Gusinaya River the following solitary and colonial corals were reported (N.M. Vasil'eva, Yu.G. Rogozov and M.F. Solov'eva, Internal Report NPO Sevmorgeologia *circa* 1974; see also Vasil'eva et al., 1974): *Favosites pseudosocialis* Dubatolov, *F.* sp. aff. *F. styricacus* Penecke, *F.* sp. aff. *F. concinnus* Kovalevsky, *F.* sp. aff. *F. breviseptatus* Smirnova, *F.* sp. aff. *F. favositiformis* Holtedahl, *F. singularis* Sokolov, *Alveolites* sp., *Stelliporella* sp. aff. *S. kaplunae* Dubatolov, *Emmonsia*(?) sp., *Syringopora* sp. aff. *S. schmidti* Tchernychev, *S. lindstromi* Tchernychev, *S.* aff. *S. gorskyi* Tchernychev, *S.* sp. aff. *S. khalganensis* Tchernychev, *Propora*(?) *incredula* Chernova, *Grabaulites* sp. aff. *G. virgulatus* Mironova, *Heliolites* sp., (identified and dated by M.A. Smirnova); and the tetracorals *Zelolasma* sp. and *Lyrielasma*(?) sp. (identified and dated by N.Ya. Spassky). This assemblage indicates an Early Devonian age.

**$S_2D_1$–F2.** Locality 1 (Fig. 2), lat. 71°06′N, long. 179°18′E. From felsenmeer some distance from the site of the $S_2D_1$–F1 collection, the following tabulate and rugose corals have been reported (N.M. Vasileva, Yu.G. Rogozov and M.F. Solov'eva, Internal Report NPO Sevmorgeologia *circa* 1974; see also Vasileva et al., 1974): *Favosites* sp. aff. *F. eichwaldi* Sokolov, *Syringopora* sp. aff. *S. schmidti* Tchernychev, *Fletcheria* sp., *Catenipora* sp., *Heliolites* sp., *Barrandelites* sp., and *Ptenophyllum* sp. (identified and dated M.A. Smirnova and N.Ya. Spassky). The presence of *Catenipora* sp. and *Fletcheria* sp. suggests a Silurian age.

**$S_2D_1$–F3.** Locality 1 (Fig. 2), lat. 71°06′N, long. 179°18′E. The following tabulates were collected, by I.M Vasil'eva and M.K. Kos'ko in 1987, from the same general locality as $S_2D_1$–F1: *Favosites plurimispinosus* Dubatolov, *F.* sp. aff. *F. socialis* Sokolov et Tesakov, *Pachyfavosites* sp. aff. *P. subnitellus* Dubatolov, *Favosites (Dictyofavosites)* sp., *Squameofavosites* sp. cf. *S. uralensis* Yanet, and *Aulocystis* sp. (identified and dated by V.P. Dubatolov). These specimens indicate an Early Devonian (Lochkovian–Pragian) age. In addition, one thin section showed an oblique section of a coral resembling *Halysites* sp. indet., suggesting the possiblity of Silurian rocks at this locality.

**$S_2D_1$–F4.** Locality 2 (Fig. 2), lat. 71°26′N, long. 179°37′E. The following fossils were collected from the Mount Drem-Khed area by G.I. Kameneva and Ya.I. Polkin in 1970: the corals *Favosites* sp. aff. *F. effusus* Klaamann, *Yacutiopora dogdensis* Dubatolov, *Rudakites* sp., *Pachyfavosites* sp. (identified and dated by M.A. Smirnova); the brachiopods *Janius* sp. and others (identified and dated by S.V. Cherkesova); the ostracods *Calcaribeyrichia*(?) sp., *Cryptophyllus* sp., *Nodibeyrichia*(?) sp., gen. indet. Primitiopsidae(?) (identified and dated by A.F. Abushik); as well as bryozoans, pelecypods, fish scales and algae. This group of fossils suggests a Late Silurian to Early Devonian age.

**$S_2D_1$–F5.** Locality 3 (Fig. 2), lat. 71°26′N, long. 179°48′E. From 40 to 60 m above the base of $S_2D_1$–Section 1. The following fossils were collected by V.G. Ganelin and A.V. Matveev in 1988: *Favosites* sp. cf. *F. similis* Sokolov, *Subalveolitella* sp. ex. gr. *repentina* Sokolov, *Syringopora* sp. cf. *S. blenda* Klaamann, *Halysites* sp. ex. gr. *catenularis* L., *Stelliporella* sp. (identified and dated by O.P. Kovalevsky); and the brachiopods *Dolerorthis* sp., *Janius*(?) sp., *Leptaena* sp., *Stegerhynchus* sp. ex. gr. *borealis* Buch (identified and dated by T.L. Modzalevskaya). The corals in this collection indicate a range of late Llandovery to Ludlow, and more likely Ludlow. Brachiopods show a broader range from Silurian to Devonian, except for *Stegerhynchus borealis*, which is typical of North American and Eurasian Wenlock to Ludlow strata.

$S_2D_1$–F6. Locality 19 (Fig. 2), lat. 71°22′N, long. 179°35′W. One type of tabulate coral was collected, by V.G. Ganelin in 1987-88, from the middle part of the Neizvestnaya River: *Favosites* sp. ex. gr. *gothlandicus* Lamarck (identified and dated by O.P. Kovalevsky). This fossil is probably Silurian in age.

## $D_{1-3}$ (Lower to Upper Devonian) Unit

**$D_{1-3}$–F1.** Locality 30 (Fig. 2), lat. 71°06′N, long. 179°34′W. From the south slopes of the Tsentral'nye Mountains, Khrustal'nyi Creek, numerous brachiopods were collected, by V.G. Ganelin in 1986, from very coarse felsenmeer. From these collections S.V. Cherkesova (pers. comm., 1989) has identified specimens from the genera *Rensselandia* and *Chascothyris*, which are known from Givetian strata of northeastern Russia.

**$D_{1-3}$–F2.** Locality 9 (Fig. 2), lat. 71°03′N, long. 179°35′W. From the headwaters of the Somnitel'naya River, the following foraminifers were reported on in Rogozov et al. (1971): *Nanicella bella* Bykova, *N. tchernyshevae* Lipina, *Tikhinella* sp. aff. *T. measpis* Bykova, *Neotuberitina maljavkini* Mikhailov, *Parathurammina* sp., *Caligella vermiculata* sp. nov., *C. borovkensis* Antropov, *Parastegnammina* sp., *Lagena* sp. aff. *L. ventricosa*(?) Bykova, *Lagena pressulla*(?) Bykova, *L. cylindrica*(?) Smith, *Corbiella depressa* Antropov, *Eotuberitina* sp., *Tikhinella* sp., *Parasteghammina* sp., *Lagena* sp. aff. *L. ventricosa*(?) Bykova, *Cochleatina*(?) sp., *Lagena* sp., *Nanicella* sp., *Earlandia* sp., *Neotuberitina maljavkini* Mikhailov, *Caligella* sp., *Parathurammina* sp. and a new species. Interpreted as likely Frasnian by M.F. Solov'eva (*in* Rogozov et al., 1971).

**$D_{1-3}$–F3.** From just north of Locality 18, lat. 71°08.5′N, long. 179°48′E, Cape Ptichii Bazar, the following foraminifers were reported by Rogozov et al. (1971): *Paracaligella* sp., *Caligella borovkensis* Antropov, *Lagena cyclindrica*(?) Smith, *Archaelagena* sp., *Lagena*(?) sp., *Schuguria* sp., *Eotuberitina* sp., *Parathurammina*(?) sp. Interpreted as likely Frasnian by M.F. Solov'eva (*in* Rogozov et al., 1971).

## $C_1$ (Lower Carboniferous) Unit

**$C_1$–F1.** From 94 to 144 m above the base of Section $C_1$–1, Locality 5 (Fig. 2), lat. 70°05′N, long. 179°15′W, headwaters of the Khishchnikov River. V.G. Ganelin and A.V. Matveev collected in 1988 the following from limestone lenses in greenish grey slate in the lower to middle part of this unit: the brachiopods Strophomenidae gen. indet., large Dictyoclostidae gen. indet., Spririferidae gen. indet. (identified and dated by V.G. Ganelin). These fossils suggest an Early Carboniferous age, no older than late Tournaisian.

**$C_1$–F2.** Various localities (M.V. Oshurkova, pers. comm., 1989). The following spores were identified: *Vallatisporites* sp., *Crassispora* sp., *Granulatisporites* sp., *Punctatisporites* sp., *Leiotriletes* sp., *Acanthotriletes* sp., *Densosporites* sp. J. Utting (pers. comm., 1991) believes these to be of latest Devonian to Early Carboniferous age.

**$C_1$–F3.** Locality 8 (Fig. 2), lat. 71°04′N, long. 179°21′W, 5 km west of the upper Khishchnikov River. The following corals were collected by V.G. Ganelin and A.V. Matveev in 1988: *Amplexus coralloides* Sowerby, *Dibunophyllum* sp. aff. *D. derbiense* Sibly, *Clisiophyllum* sp. aff. *C. reticulatum* Gorsky, *Gangamophyllum* sp., *Corwenia* sp. aff. *C. regularis* Gorsky, *Corwenia* sp. aff. *C. socialis* Gorsky (identified and dated by N.S. Kropacheva). Probable age of this collection is Early Carboniferous, Viséan.

**$C_1$–F4.** From 25 to 65 m below the $C_{1-2}$ Unit, Section $C_1$–3, Locality 8 (Fig. 2), lat. 71°04′N, long. 179°21′W, 5 km west of the upper Khishchnikov River. The following corals were collected by V.G. Ganelin in 1986: *Amplexus coralloides* Sowerby, *Dibunophyllum* sp. aff. *D. derbiense* Sibly, *Dibunophyllum* sp., *Clisiophyllum* sp. aff. *C. reticulatum* Gorsky, *Gangamophyllum* sp., *Corwenia* sp. aff. *C. regularis* Gorsky, *C.* sp. aff. *C. socialis* Gorsky (identified by G.S. Kropacheva). This collection is interpreted by V.G. Ganelin as Early Carboniferous.

**$C_1$–F5.** From Henderson et al. (1991), Geological Survey of Canada, GSC loc. C-145709. At approximately lat. 71°02′N, long. 179°16′W, north slope of the Mineeva Mountains, between the Khishchnikov and Somnitel'naya rivers, the following conodonts were recovered from a few limestone beds in a succession of clastic strata about 100 m below the $C_{1-2}$ Unit (collected by M.P. Cecile and J.C. Harrison in 1986): *Gnathodus* sp. aff. *G. delicatus*, 1 specimen and 3 indet. fragments (identified and dated by C.M. Henderson). This sample is of Early Carboniferous age. *Gnathodus delicatus* ranges from the base of the *isosticha*-upper *crenulata* Zone to the *anchoralis-latus* Zone, indicating a middle to late Tournaisian age. However, this age cannot be unequivocally assigned owing to the uncertainty of the specific identification. The conodonts appear to have been folded twice, resulting in a twisted appearance. They also have CAI values of 6–6.5, which are in the low grade metamorphic range.

**$C_1$–F6.** From Henderson et al. (1991), Geological Survey of Canada, GSC loc. C–145711. At approximately lat. 71°02′N, long. 179°10′W, north slope of the Mineeva Mountains about 51 m below the Tr Unit just east of the Khishchnikov River. One indeterminate conodont fragment was recovered (identified by C.M. Henderson, collected by M.P. Cecile and J.C. Harrison in 1986) with a high CAI value of 6.0.

**$C_1$–F7.** From Henderson et al. (1991), Geological Survey of Canada, GSC loc. C–145712. At approximately lat. 71°02′N, long. 179°10′W, just east of the central Khishchnikov River, M.P. Cecile and J.C. Harrison sampled in 1986 thin limestone beds from a mainly clastic succession. These samples yielded twenty-five small fragments of indeterminate ramiform elements, and no platform elements (identified by C.M. Henderson). The fragments exhibited anomalously low CAI values of 2.5–3.0., especially considering the high values from $C_1$–F6, 1 m below.

## $C_{1-2}$ (Lower to Upper Carboniferous) Unit

(see also Carboniferous foraminifers reported in Solov'eva, 1975)

**$C_{1-2}$–F1.** Locality 13 (Fig. 2), lat. 71°10.5′N, long. 179°06′E, 10 km from the mouth of the Gusinaya River, on the north side of the river. From a 40 to 50 m thick unit of thin bedded microcrystalline lime-mudstone, which immediately overlies $C_1$ Unit conglomerate at this location, T.A. Grunt, in 1988, collected brachiopods, bryozoans, crinoid columnals and rare gastropods. Among the specimens were the brachiopods *Stenoscisma* sp. and *Spirifer* sp. ex. gr. *kasachstanensis* Simorin 1936 (identified and dated by T.A. Grunt). The latter is known from the upper Tournaisian to Viséan strata in the Ashlyarik Suite of the Karaganda Basin.

**$C_{1-2}$–F2.** Locality 31 (Fig. 2), lat. 71°22′N, long. 179°10′E, 10 km from the mouth of the Gusinaya River, on the south side of the river. Numerous brachiopods were collected from this site by V.G. Ganelin in 1988: *Derbyia carteri* Cooper et Grant, *Tabaria rectuarita* Sarytcheva, *Reticulatia ivanovi* Lapina, *R. uralica* Tschernyschew, *Kutorginella novosemliaensis* Kalashchnikov, *Chaoiella bathycolpos* Schellwien, *Pleurohorridonia carbonaria* Kalashchnikov, *Marginifera* sp., *Sajakella martianovi* Lapina, *Fluctuaria neoundata* Mironova, *Linoproductus coralineatus* Nikitin, *L.* sp. cf. *L. tenuiliratus* Stepanov, *Purdonella praenikitini* Kalashchnikov, *Composita* sp., *Ambocoelia* sp. (identified and dated by V.G. Ganelin). These fauna have a range in age from Viséan to Serpukhovian (Early Carboniferous).

**$C_{1-2}$–F3.** Locality 18 (Fig. 2), lat. 71°08.5′N, long. 179°48′E, along the coast at the south end of Cape Ptichii Bazar. Abundant macrofauna were collected by V.G. Ganelin, in 1988, at the top of the unit from beds flanking a major bioherm. These collections included the following brachiopods: *Waagenoconcha* sp. indet., *Juressania* sp. aff. *J. juressanenisi* Tschernyschew, *Calliprotonia sterlitamakensis* Stepanov, *Urustenia*(?) sp. indet., *Fluctuaria neoundata* Mironova, *Linoproductus coralineatus* Ivanov, *L. latissimus* Ganelin sp. nov. (in collection), *Tabaria rectaurita* Sarytcheva, *Chapiella* sp. indet., *Larispirifer* sp. ex. gr. *ripheicus* Einor, *Spirifer vrangeliensis* Ganelin sp. nov. (in collection), *Neospirifer prima* Einor, *N. fasciger* Keyserling, *Beecheria* sp. (identified by V.G. Ganelin). In addition, the same collection included the following goniatites: *Phaneroceras lenticulare* Plummer et Scott, *Syngastrioceras constrictum* Nassichuk, *Aclistoceras* sp., *Trettinoceras* sp., *Diaboloceras*(?) sp., *Glaphyrites* sp. (identified and dated by M.F. Bogoslovskaya). The goniatites date the strata as middle Bashkirian (Kayalian) and likely represent the *Diaboloceras-Axinolobus* genozone.

**$C_{1-2}$–F4.** From Henderson et al. (1991), Geological Survey of Canada, GSC loc. C–145715. Locality 18 (Fig. 2), lat. 71°08.5′N, long. 179°48′E, Cape Ptichii Bazar. M.P. Cecile collected in 1986 samples from a cement/algal framestone bioherm, approximately 20 m below the contact with the overlying $P_{1-2}$ Unit, which yielded the following conodonts: *Idiognathoides marginodosus* morphotype B–1 specimen, *Neognathodus* sp. cf. *N. bothrops* – 10 specimens, *Streptognathodus* sp. aff. *S. gracilis* – 2 specimens, *Streptognathodus* sp. cf. *S. elegantulus* – 1 specimen, *Adetognathus*(?) sp. – 1 specimen, Pb, Sb, Sc elements belonging to *Neognathodus* or *Streptognathodus* indeterminate fragments; Conodont Alteration Index (CAI) of 6.0–6.5 (identified and dated by C.J. Henderson). This sample is considered to be middle to Late Carboniferous in age. Assemblages with *S. elegantulus* and *N. bothrops* have been recovered from upper Atokan (middle Moscovian) strata in Oklahoma (Grubbs, 1984). *I. marginodosus* is regarded as indicative of middle Atokan by Grayson (1984). *S. gracilis* ranges, however, from upper Desmoinesian to middle Asselian, but these forms may be a different species. An Atokan, or late Bashkherian to early middle Moscovian age is suggested. In addition, Henderson comments that these conodonts have high CAI values in the low-grade metamorphic range and appear to have been folded twice. Similar faunal assemblages have been recovered from the lower parts of the Nansen Formation, northern Ellesmere Island, Canada (A.C. Higgins, pers. comm., 1988; Henderson, 1988).

**$C_{1-2}$-F5.** Locality 32 (Fig. 2), lat. 71°04′N, long. 179°12′W, headwaters of the Khishchnikov River. The following brachiopods were reported by Chernyak and Kameneva (1976) and Kameneva and Chernyak (1973) from the $C_{1-2}$ Unit. At the base of the succession, *Fusella* sp. ex. gr. *ussiensis* Tolmachev and *Brachythuris* sp. aff. *B. peculiaris* Swallow were identified and assigned a Tournaisian age. A little higher in the section, the brachiopod *Dibunophyllum* sp. cf. *D. turbinatum* McCoy was reported (identified and dated by Yu.G. Rogozov) and assigned a Viséan age.

**$C_{1-2}$-F6.** In the areas of the upper Nasha and Khishchnikov rivers, Chernyak and Kameneva (1976) reported the following macrofauna from limestone of the $C_{1-2}$ Unit: Upper Nasha River - *Gigantoproductus* sp., *Plicatifera* sp. aff. *P. plicatilis* Sowerby, *Brachythyris* sp. cf. *D. gracilis* Phillips; upper Khishchnikov River - *Meekella* sp. cf. *M. thomasi* Janischewski. These collections were assigned a Namurian (Serpukhovian) age.

**$C_{1-2}$-F7.** From a variety of sites in the drainage areas of the Neizvestnaya and Krasnyi Flag rivers the following middle Carboniferous brachiopods were collected and identified by V.G. Ganelin in 1987 and 1988: *Buxtonia* sp. aff. *B. mosquensis* Ivanov, *Calliprotonia sterlitamakensis* Stepanov, *Juresania* sp. aff. *J. juresanesis* Tschernyschew, *Tolmatchoffia* sp. cf. *T. teniicostata* Ustritsky, *Tabaria* sp. cf. *T. rectangula* Sarytcheva, *Kutorginella novozemelica* Kalashchnikov, *Marginifera* sp. indet., *Urustenia*(?) sp. indet., *Fluctuaria neoundata* Mironova, *Linoproductus* sp., *Meristorigma paichoica* Kalashchnikov, *Choristites dilatatus* Fischer, *Larispirifer* sp. aff. *L. acuta* Einor, *L. gibba* Einor, *Brachythyrina* sp., *Eliva* sp. ex. gr. *lyra* Kutorga, *Neospirifer* sp. cf. *N. fasciger* Keyserling, *N. poststriatus* Nikitin, *Composita* sp. cf. *C. trinuclea* Hall, *Composita* sp. According to V.I. Ustritsky (pers. comm., 1992) these fossils are Middle Carboniferous in age.

The following foraminifers were collected from the same strata: *Endothyra latidorsata* Malakhova, *E.* sp. cf. *E. baschkirica* Pojarkov, E. sp. cf. *E. mosquensis* Reitlinger, *Endothyranella* sp., *Pseudoendothyra* sp., *Ozawainella angulata* Colani, *O.* sp. cf. *O. pseudorhomoboidalis* Rauzer-Chernousova, *Bradyina cribrostomata* Rauzer-Chernousova et Reitlinger, *Eostaffella acuta* Grozdilova et Lebedeva, *E. postmosquensis* var. *evoluta* Potievskaya, *E. mirifica* Brazhnikova, *Pseudostaffella gorskyi* Dutkevich, *P. antiqua* var. *grandis* Schlykova, *P. antiqua* var. *communtabilis* Reitlinger, *P.* sp. aff. *P. compressa* Rauzer-Chernousova, *Asteroarchaediscus* sp., *Tetrataxis* sp. ex. gr. *angusta* Vissarionova, *Globivalvulina moderata* Reitlinger, and *Donexella* sp. (identified by A.V. Matveev). These collections together are considered by V.G. Ganelin and A.V. Matveev to be Moscovian.

**$C_{1-2}$-F8.** Locality 16 (Fig. 2), lat. 71°16′N, long. 179°12′W, north-central part of the island. From limestone immediately overlying a succession of breccia, conglomerate and granule-sized sandstone (the clastic rocks contain abundant basic volcanic rock fragments). The limestone, collected by A.V. Matveev in 1987 and 1988, yielded the following foraminifers: *Endothyra* sp. cf. *E. mosquensis* Reitlinger, *Pseudoendothyra* sp., *Eostaffella* sp., *E. postmosquensis* Kireeva, *Ozawainella* sp., *Pseudostaffella* sp. and *Globivalvulina* sp. (identified and dated by A.V. Matveev). This collection is considered to be middle Carboniferous.

**$C_{1-2}$-F9.** From a unit 40 to 47 m above the base of Section $C_{1-2}$-1, Locality 17 (Fig. 2), lat. 71°05′N, long. 179°20′W, headwaters Khishchnikov River. Sparse tetracorals were collected by V.G. Ganelin, in 1987 and 1988, which included *Corwenia* sp. ex. gr. *minor* Yü (identified by G.S. Kropacheva). V.G. Ganelin considers this collection to be Early Carboniferous.

**$C_{1-2}$-F10.** From the basal part of a unit 442 to 507 m above the base of Section $C_{1-2}$-1, Locality 17 (Fig. 2), lat. 71°05′N, long. 179°16′W, headwaters Khishchnikov River. Strata collected by A.V. Matveev in 1987 and 1988 yielded rare specimens of the foraminifers *Planoarchaediscus stilus* Grozdilova et Lebedeva (identified by A.V. Matveev). V.G. Ganelin dates these fossils as Viséan to Serpukhovian.

**$C_{1-2}$-F11.** From a unit 515 to 553 m above the base of Section $C_{1-2}$-1, Locality 17 (Fig. 2), lat. 71°05′N, long. 179°16′W, headwaters Khishchnikov River. V.G. Ganelin collected in 1987 and 1988 large solitary and colonial corals in the lower part of the unit, and rare colonial tetracorals, zoaria and brachiopods, including strophomenids and dictyoclostids, in the upper part. The unit also yielded rare, poorly preserved specimens of the brachiopod *Schizophoria resupinata* Martin, and small unidentified productids (identified and dated by V.G. Ganelin). This assemblage is considered to be Early to middle Carboniferous.

**$C_{1-2}$-F12.** From a unit 591 to 621 m above the base of Section $C_{1-2}$-1, Locality 17 (Fig. 2), lat. 71°05′N, long. 179°16′W, headwaters of the Khishchnikov River. Limestone in this unit, collected by A.V. Matveev in 1987 and 1988, yielded the following foraminifers: *Pseudostaffella* sp. ex. gr. *gorskyi* Grozdilova et Lebedeva, *P. irinovkensis* Leontovich in Rauzer-Chernovsova et al., *P.* sp. ex. gr. *ozawai* Lee et Chen, *P. antiqua* Dutkevich, *P. subquadrata* Grozdilova et Lebedeva, *Eostaffella mirifica* Brazhnikova, *Endothyra* sp. ex. gr. *simplex* Reitlinger, *E. rzhevica* Reitlinger *Pseudoendothyra* sp., *Millerella imbicata* Kireeva, *Ozawainella* sp., *Palaeotextularia* sp., *Climacammina procera* Reitlinger, *Tetrataxis convexa* Malakhova., *Bradyina cribrostomata* Lebedeva (identified by A.V. Matveev). V.G. Ganelin dates these assembages as late Bashkirian.

**$C_{1-2}$-F13.** From a unit 621 to 671 m above the base of Section $C_{1-2}$-1, Locality 17 (Fig. 2), lat. 71°05′N, long. 179°16′W, headwaters Khishchnikov River. The following goniatites were collected by V.G. Ganelin in 1987 and 1988: *Gastrioceras* sp. cf. *G. glenisteri* Nassichuk, *Neoicoceras* sp., *Clistoceras* sp., *Gonioloboceratoides* sp., *Diaboloceras*(?) (identified by M.F. Bogoslovskaya). As with $C_{1-2}$-F3, Bogoslovskaya concludes that the goniatites date the strata as middle Bashkirian (Kayalian).

**$C_{1-2}$-F14.** From a unit 20 to 90 m above the base of Section $C_{1-2}$-2, Locality 29 (Fig. 2), lat. 71°22′N, long. 179°35′W, middle Gusinaya River. The following foraminifers were collected by A.V. Matveev in 1987 and 1988: *Archaediscus* sp. cf. *A. cornuspiroides* Brazhnikova et Vdovenko, *A.* sp. aff. *A. krestovnikovi* Rauzer-Chernousova, *A. karreri* Rauzer-Chernovsova, *Eostaffella prisca* Rauzer-Chernousova, *E.* sp. ex. gr. *psuedostruvei* Rauzer-Chernousova et Reitlinger, *E.* sp. (identified by A.V. Matveev). The following brachiopods were also collected from the same strata: *Schizophoria resupinata* Martin, *Gigantoproductus* sp., *Levicamera* sp. indet., *Punctospirifer* sp. indet., *Composita* sp. cf. *C. trinuclea* Hall. As well this unit contains abundant tetracorals and bryozoans (identified by V.G. Ganelin). V.G. Ganelin assigns these fossils a Viséan to Serpukhovian age.

**$C_{1-2}$-F15.** From a unit 90 to 110 m above the base of Section $C_{1-2}$-2, Locality 29 (Fig. 2), lat. 71°22′N, long. 179°35′W, middle Gusinaya River. Brachiopods were collected by V.G. Ganelin in 1987 and 1988 that included *Flexaria* sp. cf. *F. arcansana* Girty and *Sajakela migai* Tschernyschew (identified and dated by V.G. Ganelin). These strata are assigned a late Viséan–Serpukhovian age.

**$C_{1-2}$-F16.** From a unit 110 to ~190 m above the base of Section $C_{1-2}$-2, Locality 29 (Fig. 2), lat. 71°22′N, long. 179°35′W, middle Gusinaya River. V.G. Ganelin collected in 1987 and 1988 locally abundant, but poorly preserved brachiopods, including Dictyoclostidae and *Neospirifer* sp. indet. (identified and dated by V.G. Ganelin). These fossil groups range from Carboniferous to Permian.

**$C_{1-2}$-F17.** In the Cape Uering area, east side of the island, lat. 71°13′N, long. 177°36′W. V.G. Ganelin collected in 1987 and 1988 the following macrofossils from dolomitized carbonate: agal thalli, tubular forms of an unidentified hydroid animal, small colonies of *Syringopora*, crinoid columnals and stem fragments, all of which are abundant, and rare spirifer shells including *Palaechoristites* sp. cf. *P. subgrandis* Rotay (identified and dated by V.G. Ganelin). These strata are considered to be Tournaisian.

## $P_{1-2}$ (Lower to Upper Permian) Unit

**$P_{1-2}$-F1.** From 12 to 24 m above the base of $P_{1-2}$ Section 2, Locality 18 (Fig. 2), lat. 71°08.5′N, long. 179°48′E, Cape Ptichii Bazar. The following foraminifers were extracted from strata collected by A.V. Matveev in 1987 and 1988: *Geinitzina parva* Lipina, *G. indepressa* Cherdynzev (identified and dated by A.V. Matveev). This assemblage is interpreted as Early Permian.

**$P_{1-2}$-F2.** From 30 to 35 m above the base of $P_{1-2}$-Section 2, Locality 18 (Fig. 2), lat. 71°08.5′N, long. 179°48′E, Cape Ptichii Bazar. The following foraminifers were recovered from strata collected by A.V. Matveev in 1987 and 1988: *Protonodosaria parviformis* Gerke, *Geinitzina indepressa* Cherdynzev, *Frondicularia aktjubensis* Igonin, and others (identified and dated by A.V. Matveev). This collection is considered to be Early Permian.

**$P_{1-2}$-F3.** From approximately 100 to 150 m below the top of $P_{1-2}$ Section 4, Tundrovaya River near $P_{1-2}$ Section 3. Locality 22 (Fig. 2), lat. 71°19.5′N, long. 179°52′W. The following macrofossils were collected by V.G. Ganelin in 1987 and 1988 from coquina beds:

small productids, gastropods, *Spiriferella* sp. indet., *Sowerbina* sp. indet., and from farther along strike, large fragments of *Kolymia* (identified and dated by V.G. Ganelin). These fossils are assigned a Permian age. The following foraminifers were recovered from collections made by A.V. Matveev from limestone beds in this interval: *Nodosaria* sp. cf. *N. cassiaformis* Igonin, *Geinitzina* sp. aff. *G. postcarbonica* Spandel, *Frondicularia* sp., *Rectoglandulina borealis* Gerke, *Pseudonodosaria starostinaensis* Sosipatrova (identified and dated by A.V. Matveev). These two collections are considered to be of Late Permian age.

**$P_{1-2}$-F4.** From 160 to 230 m above the base of $P_{1-2}$ Section 3, Locality 19 (Fig. 2), lat. 71°22′N, long. 179°35′W, middle Neizvestnaya River. The following foraminifers were recovered from strata collected by A.V. Matveev in 1987 and 1988: *Geinitzina* sp. nov., *Nodosaria* sp., *N. lata* Sosipatrova, *N.* sp. ex. gr. *spitzbergiana* Sosipatrova, *Frondicularia* sp. aff. *F. reliqua* Gerke, *Dentalina* sp. (identified and dated by A.V. Matveev). These fossils are considered to be of Permian age.

**$P_{1-2}$-F5.** From 180 to 150 m below the top of $P_{1-2}$ Section 5, Locality 23 (Fig. 2), lat. 71°21′N, long. 179°32′W, east bank, middle Neizvestnaya River. The following brachiopods were collected by V.G. Ganelin in 1987 and 1988: *Waagenoconcha payeri* Toula, rare *Kuwelousia weiprechti* Toula, *Spiriferella* sp. indet. (identified and dated by V.G. Ganelin); in addition, strata collected by A.V. Matveev from the same unit yielded the foraminifers *Protonodosaria proceraformis* Gerke and *Pseudonodosaria* sp. (identified by A.V. Matveev). All the brachiopods are typical of the Kazanian-Tatarian, Late Permian suites.

**$P_{1-2}$-F6.** From 110 to 135 m above the base of $P_{1-2}$ Section 5, Locality 23 (Fig. 2), lat. 71°21′N, long. 179°32′W, east bank, Middle Neizvestnaya River. A brachiopod of the family Horridonidae gen. et sp. indet. was collected by V.G. Ganelin in 1987 and 1988 (identified and dated by V.G. Ganelin). This type of brachiopod is considered to range from Carboniferous to Permian.

**$P_{1-2}$-F7.** From basal 160 m thick breccia unit, $P_{1-2}$ Section 3, Locality 19 (Fig. 2), lat. 71°22′N, long. 179°35′W, middle Neizvestnaya River. A single brachiopod was recovered from a limestone block by V.G. Ganelin in 1987 and 1988: *Spiriferella* sp. indet. (identified and dated by V.G. Ganelin). Age range of this genus is Late Carboniferous to Permian.

**$P_{1-2}$-F8.** From 290 to 390 m above the base of $P_{1-2}$ Section 1, Localities 20, 21 (Fig. 2), lat. 71°03.5′N, long. 179°11′W and lat. 71°03.5′N, long. 179°09′W, headwaters area Khishchnikov River; and 160 to 230 m above the base of $P_{1-2}$ Section 3, east bank of the middle Neizvestnaya River, Locality 23 (Fig. 2), lat. 71°21′N, long. 179°32′W.

V.G. Ganelin collected detrital fragments of the bivalve *Kolymia* (identified by V.G. Ganelin). Chernyak and Kameneva (1976) and Kameneva and Chernyak (1975) also identified *Kolymia*. *Kolymia*-bearing units found on Wrangel Island are considered correlative with the Dzhigdalinskaya Suite of northeastern Russia. In recent Soviet literature the Dzhigdalinskaya Suite is correlated with an upper stage (Kungurian) of the Early Permian in northeastern Russia (Eliseeva et al., 1984). W.W. Nassichuk (pers. comm., 1991), feels however that *Kolymia* may be Early or Late Permian in age.

## Tr (Triassic) Unit

**Tr-F1.** From the southeast part of the island near Utyos Bol'shevik Point (between the outlet of the Klark River and Cape Pillar (Fig. 2), the following pelecypods have been reported by Ivanov (1973) and Til'man et al. (1970) from argillaceous sandstone: *Halobia* ex gr. *superba* Mojsisovice, *Monotis scutiformis* var. *M. typica* Kiparisova, *M. pinensis* Westermenn and *M. setacanensis* Kiparisova. The fossils were identified as Norian.

**Tr-F2.** At the outlet of a small tributary feeding into the Klark River, near the southeast coast (Fig. 2). From argillaceous siderite nodules believed to have been transported downstream from upland exposures of Triassic sandy slate the following peleycpods have been reported by Til'man et al. (1970): *Monotis jakutica* Teller, *M. ochotica* var. *M. densistriata* Teller and *M.* sp. aff. *M. subcircularis* Yabb. These fossils were dated by Til'man et al. (1970) as Carnian but Bychkov (1991) assigned this group of fossils to Middle and Late Norian.

## PN (Paleogene-Neogene) Unit

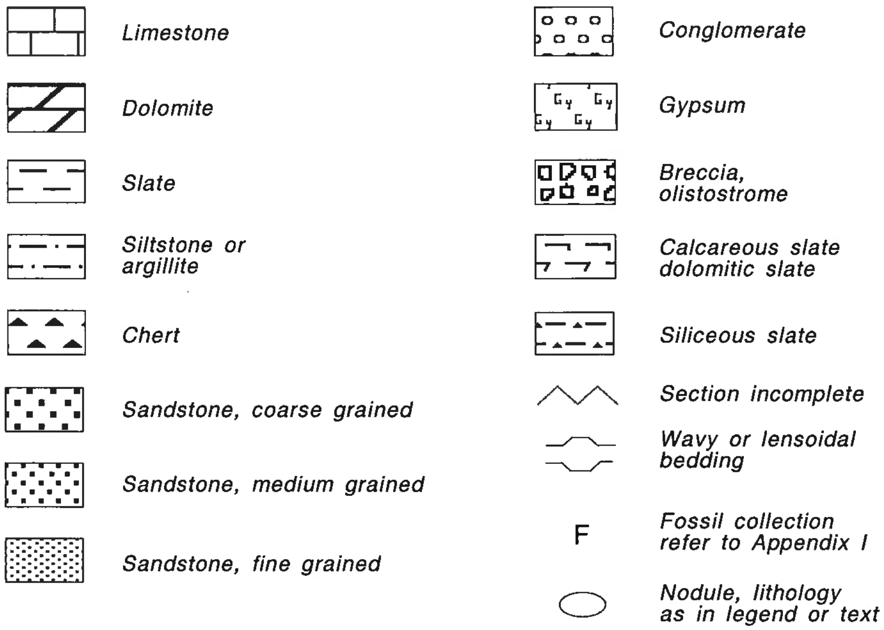
**PN-F1.** From exposures on the lower Tundrovaya River area (Fig. 9), the following foraminifers have been identified in thin section: Order Rotalida (possibly genera *Cibicides* or *Ammonia)*, Families Nonionidae(?), Polymorphinidae and Nodosariidae(?) (Pleurostomellidae?) (identified by V.A. Basov and V.Y. Slobodin, collected by O.N. Vinogradova) Basov and Slobodin (pers. comm., 1988) noted that some forms suggest a Late Paleogene or even Neogene age.

From the same locality, Avdyunichev and Volodin (1989) identified the following pollen: Angiosperms – most were *Betula*, Ericaceae, *Alnus* but a few, *Myrica* (3.8%) and *Juglans* (2.8%), are typical of the Neogene; also the forms *Triatriopollenites*, *Tetraporites*, *Tricolpites,* which are widespread in the Late Cretaceous and Paleogene; Gymnosperms – Pinaceae, *Ginkgo*, *Podozamites*, *Pinus*. Avdyunichev and Volodin (1989) also identified the following spores: Gleicheniaceae (*Plicifera* and *Clavifera* – 10.3%) and a smaller number of Schizaeaceae, Dipteridaceae, Hausmannia, and a few single specimens of *Sphagnites*, *Osmundacidites*, *Coniopteris*, *Leiotriletes*, *Selaginella*, Polypodiaceae. The majority of the spores are found in the Cretaceous and Paleogene. Avdyunichev and Volodin (1989) date the spores and pollen as Paleogene(?)–Neogene.

# APPENDIX 2

## Stratigraphic sections

### Legend for stratigraphic figures in Appendix 2 and in text



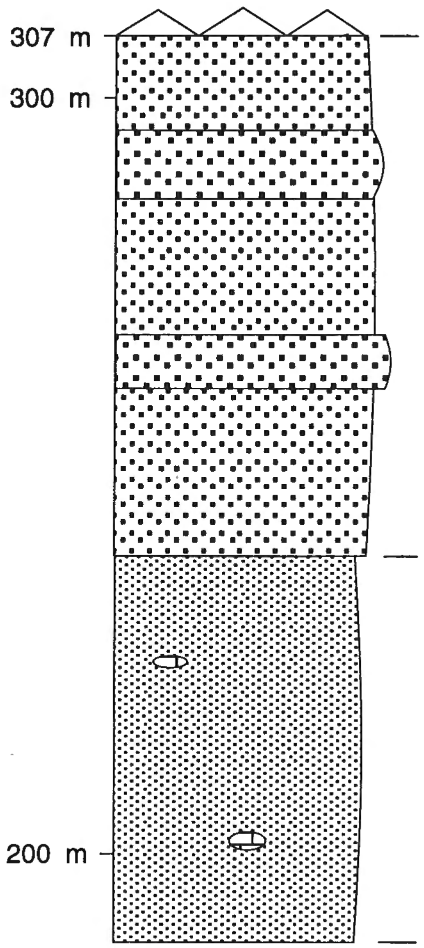

Note that many units on stratigraphic columns are combinations of symbols shown above. Refer to Appendix text for details.

**TABLE OF FORMATIONS**

| Age | Unit | Lithology |
|---|---|---|
| Quaternary | Unnamed | Coarse clastic alluvium, proluvium, eluvium and colluvium. |
| Late Tertiary | Unnamed | Indurated Pliocene mud and gravel (a few metres). |
| Tertiary Paleogene–Neogene | PN | Clay and gravel (a few tens of metres thick). |
| Triassic | Ŧ | Black to dark grey argillaceous quartz turbiditic sandstone with minor feldspar and lithic fragments, black slate; minor siltstone (total thickness estimated to be 800–1500 m). |
| Permian | $P_{1-2}$ | Slate and limestone with minor sandstone, coarse clastic and siliceous strata; in the north the basal part contains a thick olistostrome-breccia succession (up to 750 m thick). |
| Carboniferous | $C_{1-2}$ | Two facies types: 1) microcrystalline and crinoidal biocalcarenite, fine grained, thin bedded limestone, and minor slate and argillite; 2) limestone interstratified with slate and argillite (up to 1400 m thick). |
| Lower Carboniferous | $C_1$ | Clastic rocks, including intrabasinal conglomerate, slate, argillite, with gypsum and carbonate (up to 350 m thick). |
| Devonian | $D_{1-3}$ | Immature clastic rocks, including sandstone, argillite, slate and conglomerate (as much as 1200 m thick). |
| Silurian–Devonian | $S_2D_1$ | Fossiliferous quartzose sandstone, siltstone, slate, carbonate (total thickness=700 m) |
| Upper Proterozoic | Wrangel Complex | Felsic to intermediate volcanic and volcaniclastic rocks, sericitic and chloritic slate/schist with minor grey and black slate, and very minor mafic metavolcanics, quartzite, and metaconglomerate; intruded by quartz-feldspar porphyry, metagabbro, metadiabase, and aplitic felsic dykes and sills and small elongate granitic and aplitic intrusive bodies (total thickness=>2000 m). |

## $S_2D_1$ (Upper Silurian–Lower Devonian) Unit

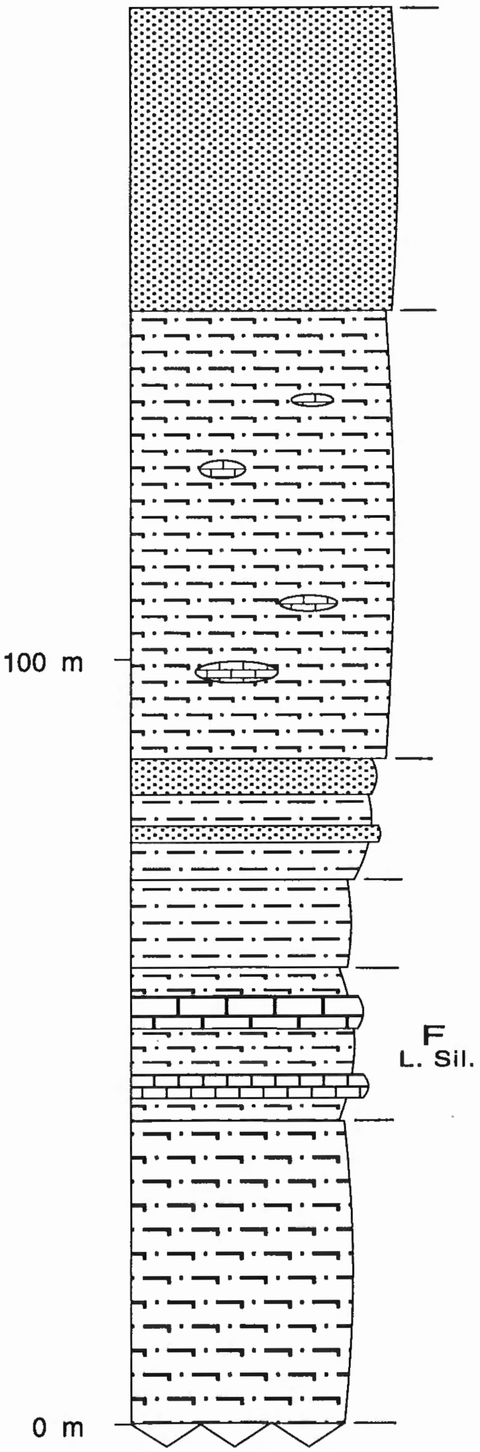
**$S_2D_1$ Section 1.** A section of the basal $S_2D_1$ Unit measured on the northern slope of Mount Maly Drem-Khed. Locality 3 (Fig. 2). Middle of section at lat. 71°26′N and long. 179°48′E (also illustrated in Fig. 17).




covered

70 m of **sandstone**: fine to medium grained, foliated, polymictic, with thick massive beds

50 m of **sandstone**: greenish grey, fine grained, well indurated, with thin, parallel or crosslaminae defined by alternations of fine grained, grey laminae and coarse grained, yellow-brown laminae; minor lenses of grey calcarenite with gastropods and rare tabulate corals




40 m of **sandstone**: grey, thin bedded and crossbedded, fine grained, with large ripples at the base; fragments of tabulate corals are common

60 m of **sandstone**: grey and greenish grey, calcareous, massive and slaty, fine grained, with lenses of crinoidal calcarenite containing fragments of tabulate corals

15 m of polymict **siltstone** giving way to **sandstone** upsection; with crossbeds and ripples

10–12 m of **siltstone**: greenish grey, platy

20 m of **siltstone**: grey, calcareous, with thick units of **limestone**; the abundance of limestone increases upsection; contains corals and brachiopods of collection $S_2D_1$–F5, typical of Upper Silurian (Wenlock to Ludlow)

40 m of **siltstone**: grey, calcareous, polymict

base not observed

## $D_{1-3}$ (Lower to Upper Devonian) Unit

**$D_{1-3}$ Section 1.** Complete section measured on the north side of the Gusinaya River. Locality 4 (Fig. 2). Center of section at lat. 71°12′N, long. 179°10′E (illustrated in Fig. 19).

- overlain by the $C_1$ Unit
- 200–700 m of **sandstone and slate**: fine grained, grey, foliated, immature, containing thin beds of siltstone and fine grained sandstone, and thick units of black, cherty slate and well indurated siliceous rock; (this upper unit is poorly exposed and cannot be accurately measured; it is estimated to be between 200 and 700 m thick)
- approximately 300 m of **sandstone:** fine to coarse grained, grey, immature, with minor amounts of siltstone and argillite; current structures are common
- 150–200 m of **quartzite**: medium to coarse grained, yellow-grey or brownish; in the upper part are rare grit and conglomerate with small quartz pebbles; the strata are massive and featureless but some are platy parted; rare clasts of acidic volcanic rocks have been identified; (this is essentially the Eskimoskaya Suite of Lobanov, 1957)
- basal contact with $S_2D_1$ approximately at this level but not observed

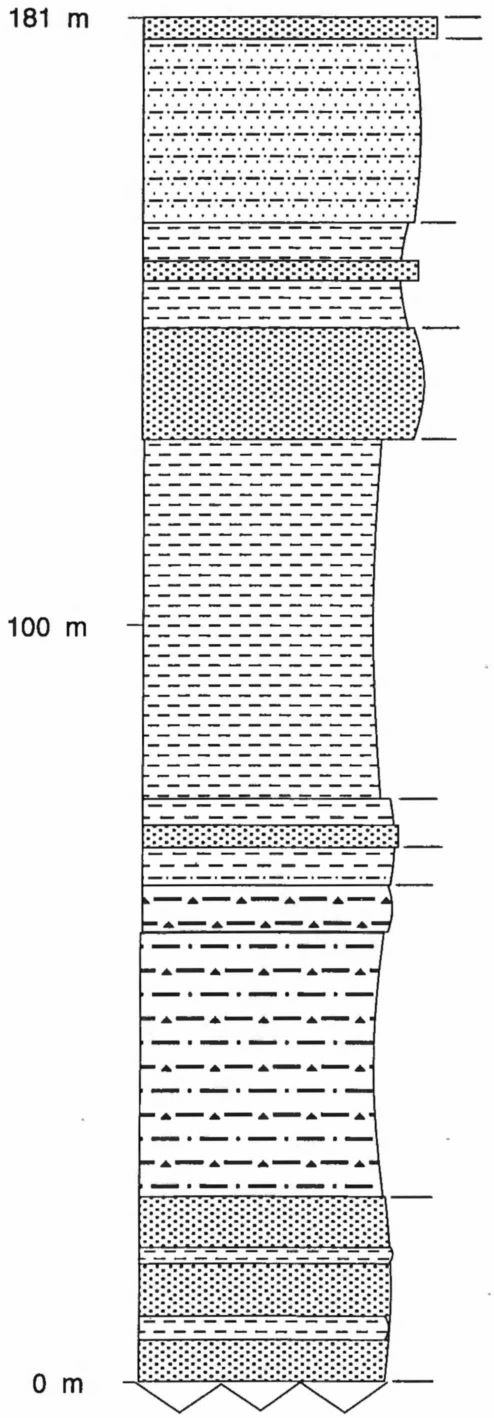
**$D_{1-3}$ Section 2.** The following succession was measured in the Mount Drem-Khed area. Locality 3 (Fig. 2). Center of section at lat. 71°26′N and long. 179°48′E.

- upper contact not observed
- an upper unit of **slate**: black, and **sandstone**: immature, well sorted, fine to medium grained (thickness unknown)
- 300–350 m thick lower unit of **quartzite** and **quartz sandstone**: greenish grey or pink-grey; this includes minor beds of red argillite, calcareous argillite, and grit
- approximate position of the lower contact traced in felsenmeer

**$D_{1-3}$ Section 3.** Complete section measured on the southern slopes of the Tsentral'nye Mountains. Locality 5 (Fig. 2). Center of section at lat. 71°05′N, long. 179°15′W (illustrated in Fig. 19).

- overlain by the $C_1$ Unit
- 16 m of **argillite**: green, slaty; with thin beds of gritstone and sandstone
- 30 m of **sandstone**: coarse grained to gritty, greenish grey with thin beds of pink-grey sandstone
- 100 m of **siltstone**: foliated, cherty, green, interbedded with **sandstone**: fine grained, greenish grey
- 60 m of quartz and feldspar-quartz grit interstratified with **argillite**: micaceous, thin bedded, green
- 170 m of quartz grit and sandstone with some feldspar grains, and minor, green, slaty argillite. The upper part shows graded bedding in thin to thick beds
- 70–80 m of talus cover
- 30–60 m thick lower unit of pebble to cobble conglomerate. Clasts are well rounded and 80% resemble lithologies found in the Wrangel Complex
- underlain by the Wrangel Complex

**$D_{1-3}$ Section 4.** Incomplete section measured on the west bank of the upper Khishchnikov River, piedmont of the Mineev Mountains. Locality 10 (Fig. 2). Lat. 71°02′N, long. 179°18′W.




Tr Unit clastic rocks

3 m of **sandstone**: black, massive, fine grained

24 m of **sandstone** and **silstone**: black to dark grey, generally thin bedded, fine grained, with very thin beds of **slate**; some sandstone beds are thick

13–15 m of **slate**: black, with isolated thin beds of grey **siltstone** and fine grained **sandstone**

15 m of **sandstone**: dark grey, fine grained, massive and flaggy, and **sandstone**: silty, with very thin beds of slate

47 m of **slate**: black to dark-grey

11 m of **sandstone**: thin-bedded, fine grained, with thick units of siliceous **slate** with siltstone laminae; graded bedding

7 m of **slate**: black, siliceous, micaceous, with minor siltstone laminae

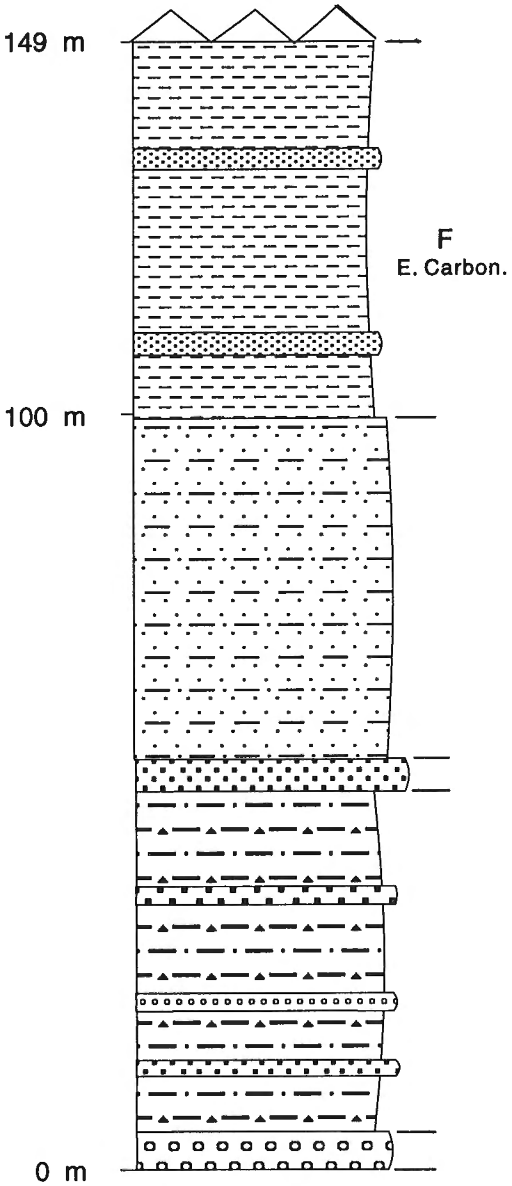
35 m of **siltstone** and siliceous-micaceous **slate**: thin and very thin bedded, ripple marks and current lineations

24 m of **sandstone**: fine grained, greenish grey, thin bedded, with very thin beds of slate, pyrite crystals

covered

## $C_1$ (Lower Carboniferous) Unit

**$C_1$ Section 1.** Section measured in the basal half, Upper Khishchnikov River. Locality 5 (Fig. 2). Lat. 71°05′N, long. 179°15′W (also illustrated in Fig. 25).




covered

50 m of **slate**: grey, greenish grey, with rare beds of sandstone up to 20–30 cm thick; brachiopods of collection $C_1$–F1 (Early Carboniferous) are from this succession

45 m of **sandstone**: pinkish grey, fine to coarse grained, with interbeds of grey and pinkish grey **slate** and slaty **siltstone**; rounded chert clasts up to 4 cm in diameter are found in the lower parts of the sandstone; interbeds are 2–60 cm thick

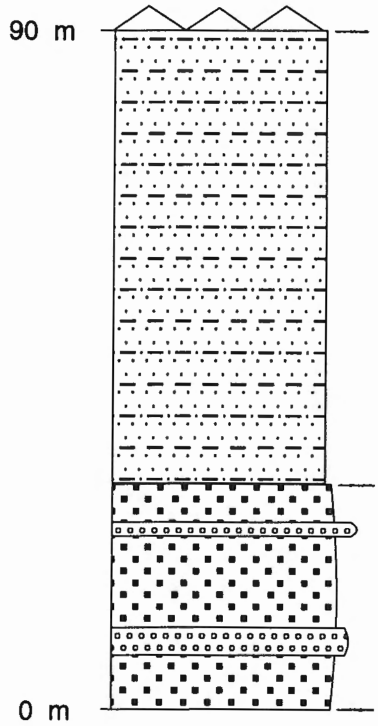
4 m of **sandstone**: massive, grey, well indurated, medium to coarse grained

45 m of **argillite**: dominantly silty, chloritic and siliceous, interbedded with sandstone, granule-sized sandstone and conglomerate; some coarse grained beds are 50 cm thick

5 m of **conglomerate**: boulder to fine pebble grade; clasts are rounded and angular and consist of quartzite, quartz sandstone, quartz, and siliceous argillite; interstratified with the conglomerate are beds of coarse grained sandstone

$D_{1-3}$ Unit

**$C_1$ Section 2.** Section in the basal part of the unit, Upper Khishchnikov R. 1.5 km west of Section $C_1$–1. Locality 6 (Fig. 2). Lat. 71°05′N, long. 179°18′W (also illustrated in Fig. 25).



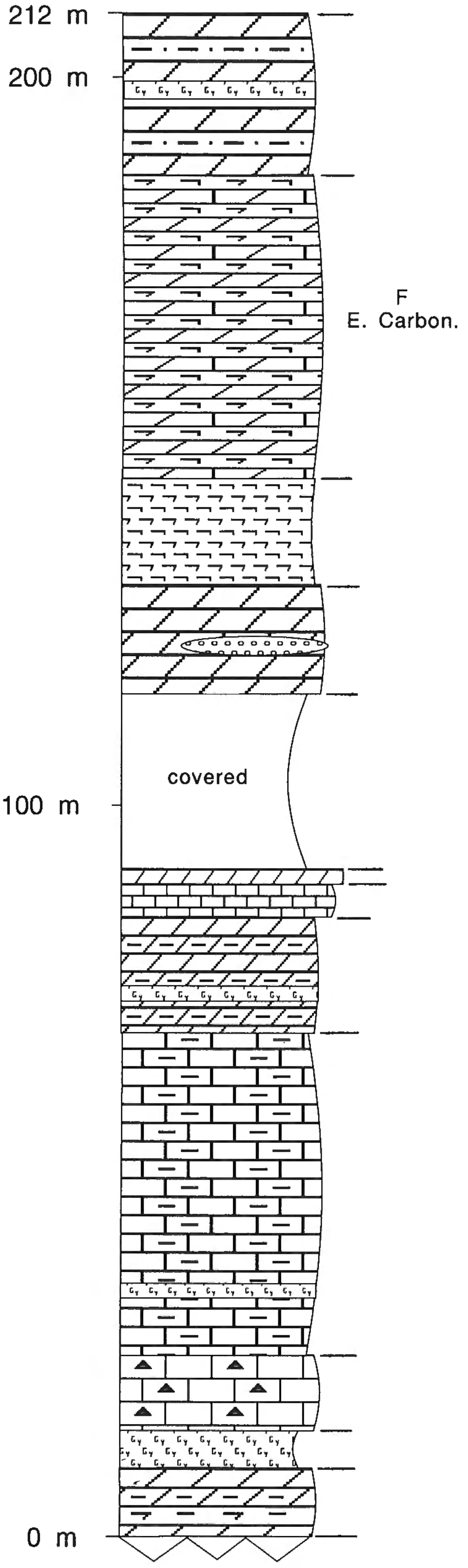

covered

approximately 60 m of **sandstone**: grey to light pinkish grey, fine to medium grained, interbedded in thin to thick beds with **mudstone** and **chloritic argillite**; sandstone is slightly dominant, and consists of quartz and feldspar with varying amounts of carbonate; rare thin beds of granule-sized sandstone

15–30 m of **sandstone**: poorly sorted, pinkish grey, with minor variegated pebble to boulder **conglomerate** (1.5 km farther west this conglomerate is 20 m thick and varies in size from pebbles to boulders up to 20 cm; here the clasts are dominated by light grey and maroon quartzite and quartz, and there are rare clasts of veined, brecciated and fractured quartzite and green argillite that resemble the underlying $D_{1-3}$ Unit; the clasts are suspended in a matrix of silica-cemented quartz sand with minor plagioclase)

$D_{1-3}$ Unit

$C_1$ **Section 3.** Section measured in the upper half of the unit, 5 km west of the upper Khishchnikov River. Locality 8 (Fig. 2). Lat. 71°04′N, long. 179°21′W (also illustrated in Fig. 25).




25 m of thinly to thickly interbedded varicoloured, friable **silty claystone**, milky-white to yellowish **gypsum** (in felsenmeer only) and argillaceous **dolomite**

30–40 m of **dolomite**: parallel-laminated, calcareous, and dolomitic and calcareous **mudstone**; near the top of the unit are massive, light grey, siliceous quartzitic dolomite beds as much as 10 m thick; corals from collection $C_1$–F4 (Early Carboniferous) were gathered from this succession

15 m of **mudstone**: thin bedded green and brick-red, dolomitic, calcareous, with oolites and brachiopod shell detritus

1 m of unconsolidated silty **clay** and a thick bed of gypsum

15 m of **dolomite**: thinly to thickly interbedded green, dark grey and brick-red; minor lensing thick beds of granule to fine-pebble conglomerate with rare boulder sized clasts; clasts consist of quartz and quartzite suspended in a carbonate-clay-cemented sandstone matrix

25 m covered

3 m of **dolomite**: fine grained, green, platy dolomite

4 m of **limestone**: fine grained, dark grey to black, platy limestone

16 m of thinly interbedded dolomite, and green and brick-red argillaceous dolomite, with minor thick to very thick gypsum beds

44 m of **limestone**: platy, light grey, argillaceous, with 1 m unit of milky white **gypsum** in the lower part

10 m of **limestone**: massive, porous, grey, siliceous, cut by numerous veinlets of calcite

6 m of **gypsum**: milky white, with interbeds of dolomitic, calcareous mudstone like that described below

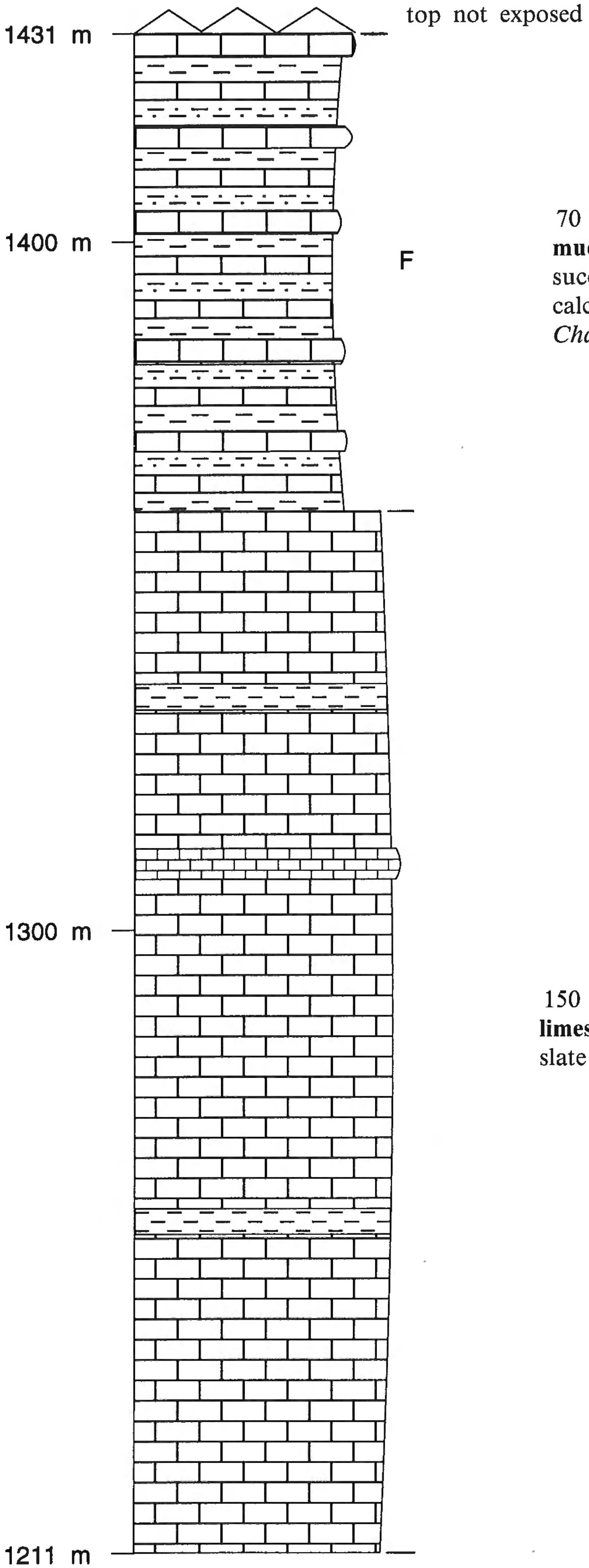
approximately 8 m of interbedded **dolostone**: fine grained, medium bedded, rusty green weathering, **dolomite**: thin bedded, argillaceous; **mudstone**: dolomitic, calcareous, and **mudstone**: thin to very thin bedded, green

Overlies the lower part of the $C_1$ Unit

## $C_{1-2}$ (Lower to Upper Carboniferous) Unit

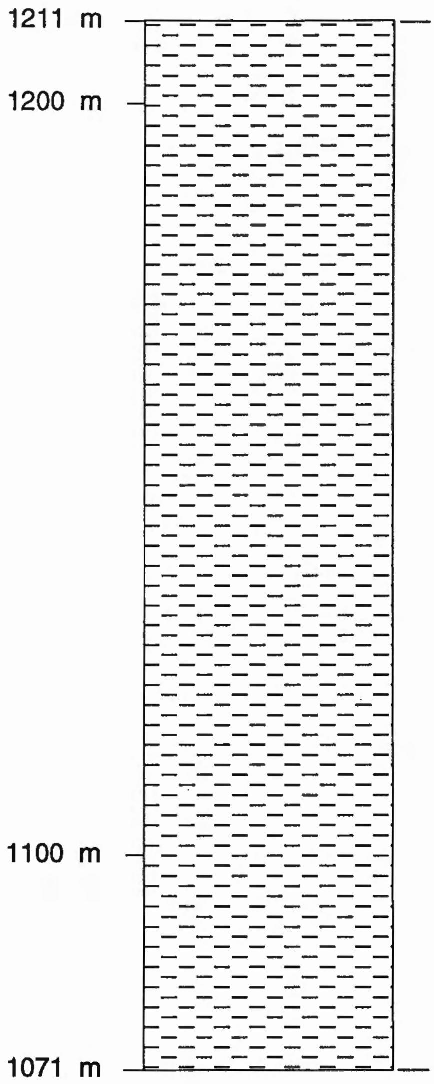
**$C_{1-2}$ Section 1.** A composite of three incomplete sections from a single monoclinal structure in the headwaters area of the upper Khishchnikov River. Locality 17 (Fig. 2). Three sections all with lat. 71°05′N, and long.'s 179°12′, 179°16′, 179°20′- all co-ordinates for bases of incomplete sections; also illustrated in Fig. 33).

**N.B.** The measured thickness of this section is about twice as thick as is apparently possible from structural analysis (Fig. 51). The most probable source of error was in measuring, but errors in assembling the section, or real lateral variation in thickness are other possibilities. This discrepancy will only be solved when the section is remeasured.

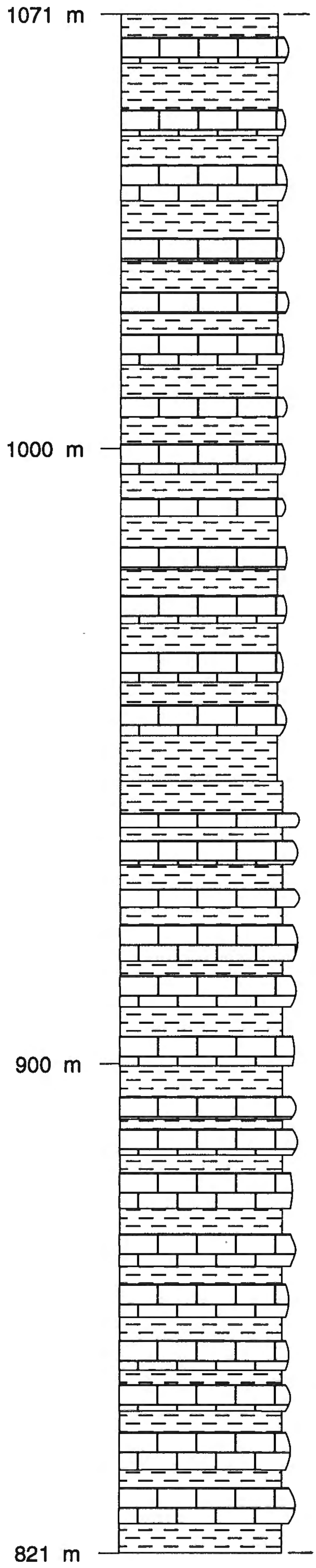



70 m of interstratified black **slate, limestone,** and green **mudstone** in 0.5–1.5 m thick units; slate dominates the succession; the limestone is crinoidal and varies from a calcarenite to fine grained; in the upper part are fragments of *Chaetetes* coral colonies and small tetracorals

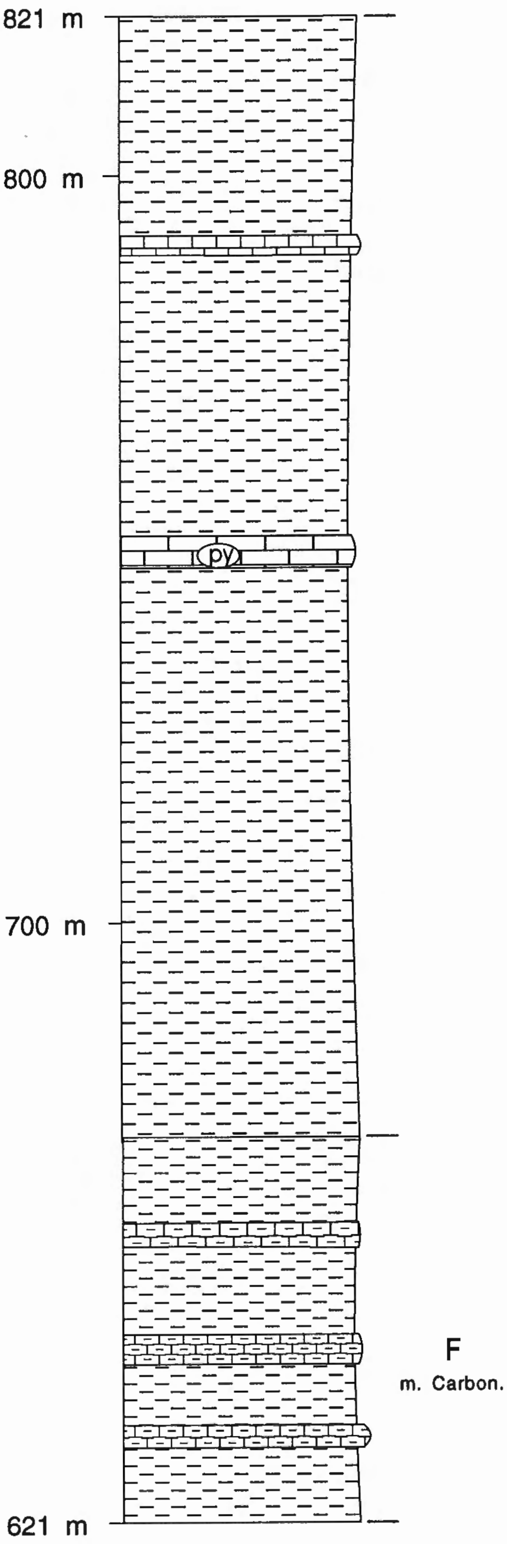
150 m of **calcarenite**: crinoidal, and rare, fine grained **limestone** in units up to 2.5 m thick, with minor units of black slate 1-6 m thick




140 m succession of **slate**: monotonous, black

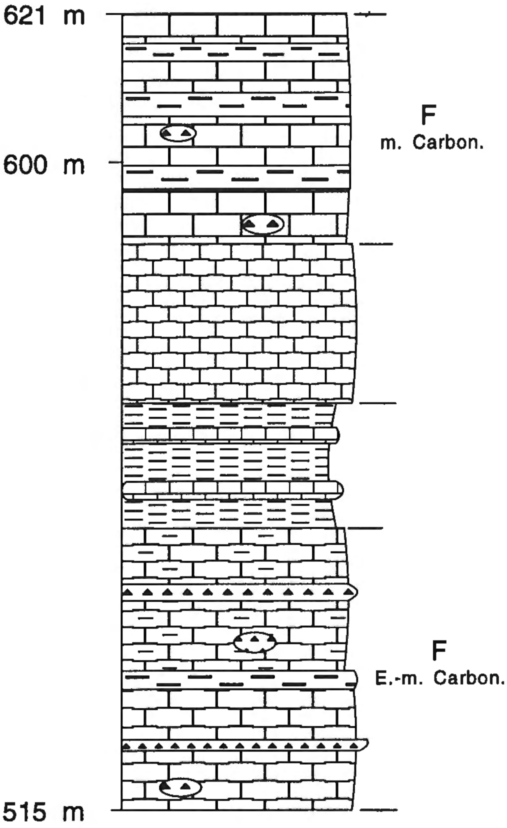



250 m of interstratified **limestone**: 5–20 m thick units and **slate:** 3–5 m thick units, black; the limestone is a biocalcisiltite with crinoids; limestone dominates the lower part of the unit; slate and limestone are equally abundant in the upper part of the unit




150 m succession of **slate**: monotonous, black; rare, thin, and even rarer, thick beds, of **limestone**: fine grained, grey, with finely dispersed pyrite and numerous, lump-shaped pyrite nodules up to 4 cm in length

50 m of **slate**: dark green, apple-green to yellow, weathers bluish grey; with beds and units of argillaceous, crinoidal **limestone; breccia**: slate matrix with abundant clasts of slate, black chert, crinoids and rare limestone, up to 2 cm in size; the limestone is laminated and wavy laminated and occurs in thin to medium thick beds and in two units 3 m and 5 m thick; ammonoids described in collection $C_{1-2}$-F13 are from this unit, and are considered to be middle Carboniferous (middle Bashkirian) in age

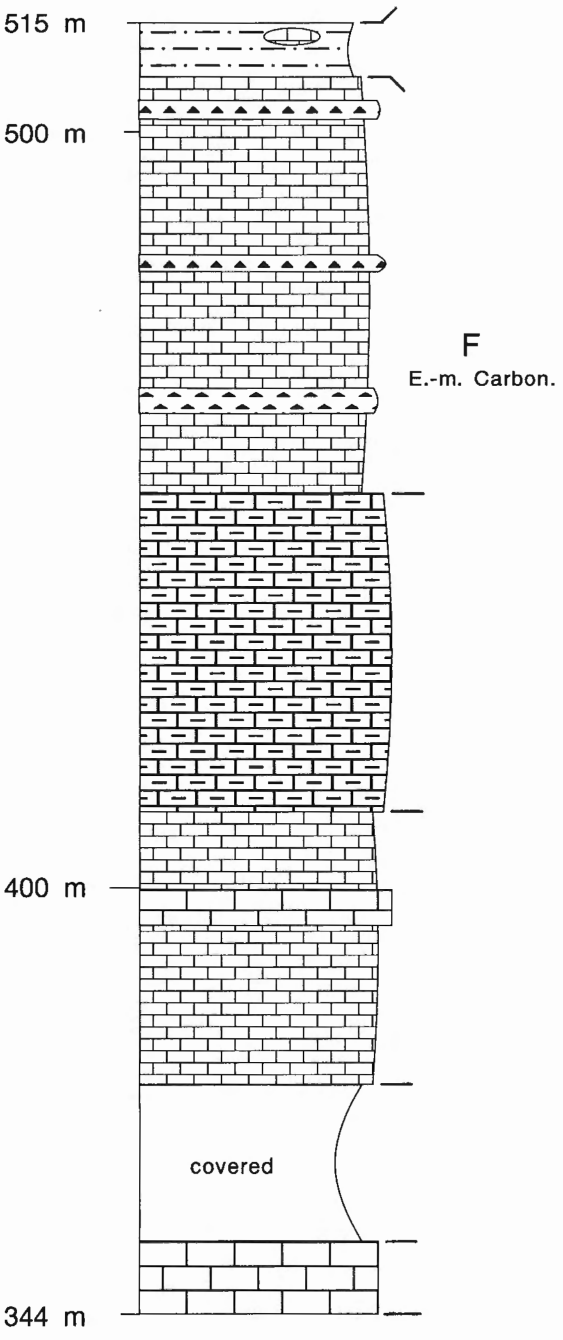



30 m of **limestone** and **slate**: limestone is thin to thick bedded, consists of grey, crinoidal calcarenites with crinoid columnals up to 1.2 cm and contains lenses of black chert; the slate is subordinate, black, and greenish to light grey; slate units are 0.3 to 0.5 m thick. The number and thickness of slate units increase upward; contains foraminifers described in collection $C_{1-2}$–F12 (middle Carboniferous, late Baskhirian)

20 m of **limestone**: variegated, thin and wavy bedded, crinoidal

18 m thick succession consisting of 4–5 m thick units of black **slate** interstratified with thin beds, and 1.5–2 m thick units, of **limestone**: crinoidal

38 m thick succession of **calcarenite**: fine grained, lenticular, with beds of fine grained **limestone**: calcarenite with columnals up to 1–1.2 cm in diameter; unit is massive in the lower part and shaly in the upper part; some lenses are 2–2.5 m thick; throughout the entire succession are thin beds and nodules of black chert, and in the middle part, black slate; contains abundant solitary and colonial corals and rare, poorly preserved brachiopods, collection $C_{1-2}$–F11 (Early to middle Carboniferous)




6.5 m of **slate**: green, silty, with interbeds and lenses of grey limestone; minor thin beds of granule to fine pebble **conglomerate** composed of quartz and chert clasts

1.5 m of **conglomerate**: subangular, fine pebble, 40% quartz and chert clasts suspended in a matrix of green, calcareous sandstone and siltstone

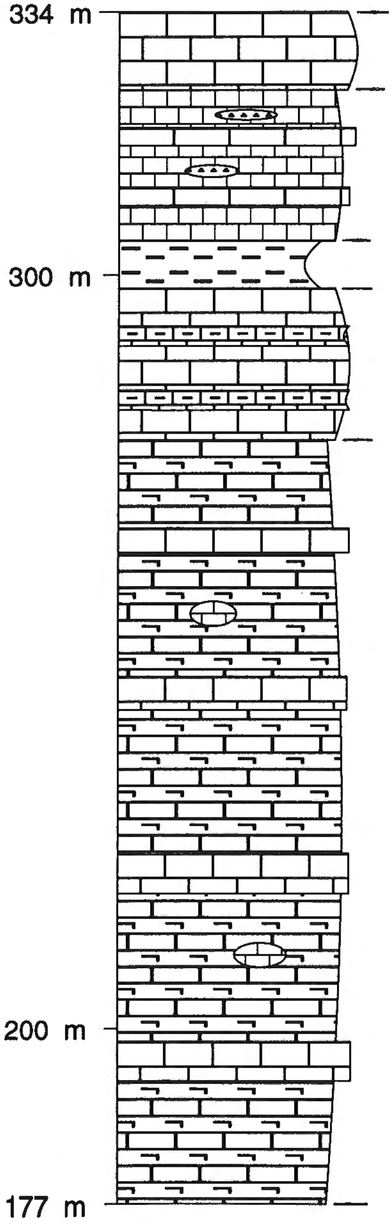
65 m of **limestone**: fine grained, dark grey, thin bedded to massive, microcrystalline, with thin beds of black chert; rare foraminifers in the lower part $C_{1-2}$–F10 (Early to middle Carboniferous, Viséan to Serpukhovian)

43 m of **calcarenite**: massive slaty crinoidal; white at the base of the unit

35 m of **limestone**: dark grey to black, fine grained, microcrystalline, thin bedded and foliated, with dispersed thick beds and units of crinoidal calcarenite

20 m covered

10 m of **limestone**: dark grey, bituminous, fine grained, poorly bedded



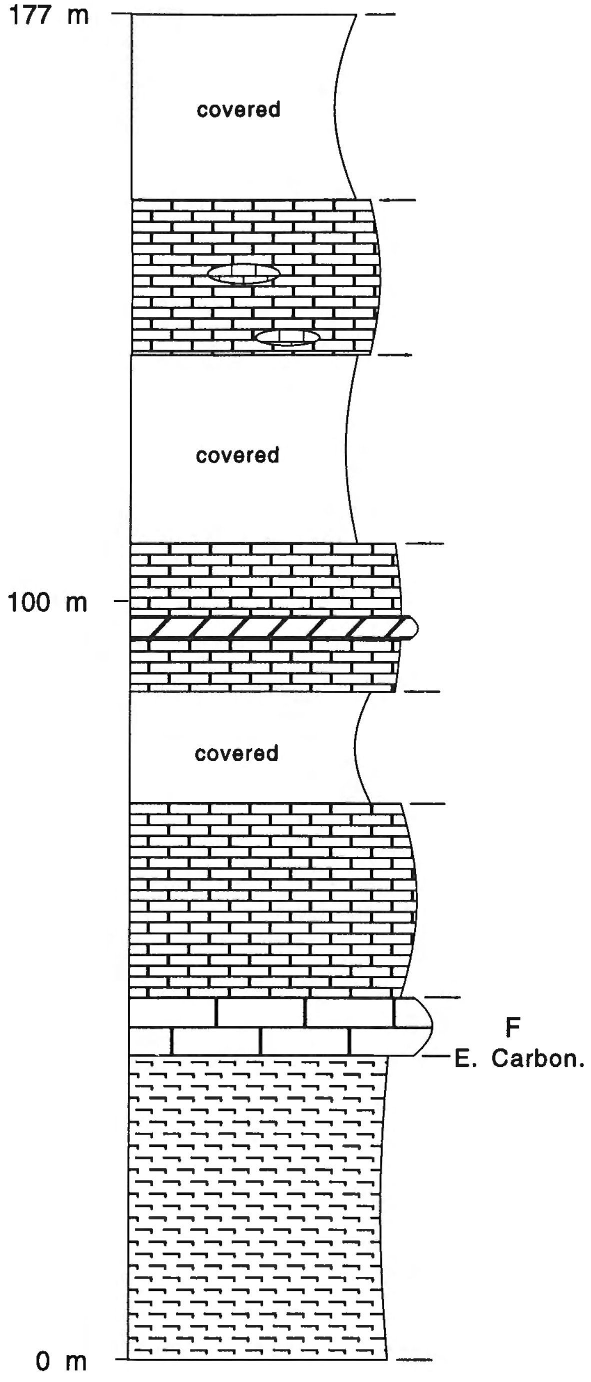

10 m of **calcarenite**: massive and foliated, white weathering, crinoidal; and microcrystalline **limestone**

13–20 m of interstratified succession of **limestone**: thin to thick bedded, fine grained, dark grey to black, poorly bedded and foliated, and crinoidal **calcarenite,** with thin beds and lenses of black chert; the abundance of crinoidal limestone increases upward in the unit

7 m of **slate**: black, calcareous, papery, with rare, thick beds of **limestone**: coarse grained, grey

18–20 m thick interstratified succession of **limestone**: poorly stratified, thin to medium bedded, granular, grey; **limestone**: foliated, shaly; and **limestone**: thick-bedded, granular

100 m of **mudstone**: fine grained, microcrystalline, dark grey, thin bedded and foliated, and **mudstone**: calcareous, with thin to thick beds and lenses of grey and light grey, coarse grained, crinoidal **limestone**, and rare, very thin beds of variegated mudstone




25 m covered

20 m of **limestone**: fine grained, dark grey, thin bedded and foliated, with lenses of **limestone**: massive, coarse grained, crinoidal, up to 2 m thick

25 m covered

20 m of **limestone**: fine grained, dark grey, thin bedded and foliated, with beds of granular **dolomite** up to 0.5 m thick

15 m covered

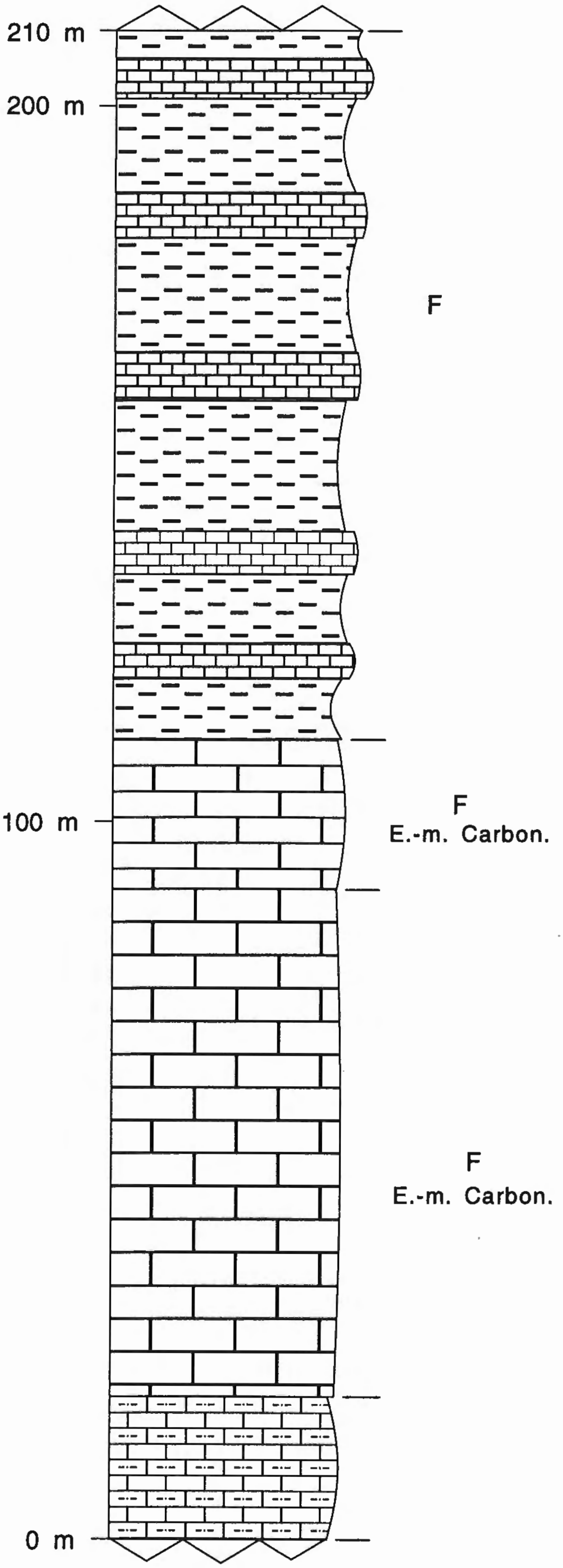
25 m of **limestone**: fine grained, dark grey, thin bedded and foliated with beds of light grey, crinoidal **calcarenite**

6–7 m of **calcarenite**: crinoidal, with poorly defined, thick and lenticular bedding; includes tetracorals of collection $C_{1-2}$–F9 (Early Carboniferous)

40 m of **mudstone**: dark grey, foliated, calcareous, with thin beds of massive, dark grey limestone

$C_1$ Unit - Upper part with gypsum and carbonate

**$C_{1-2}$ Section 2.** Section measured along the north side of the Gusinaya River, 13 km from its mouth. Locality 29 (Fig. 2). Lat. 71°22′N, long. 179°35′W.




covered

80–100 m of **slate**: black, with numerous thin to medium beds of **limestone**; in places with poorly preserved brachiopods, collection $C_{1-2}$-F16 (Carboniferous to Permian)

20 m of **limestone**: the lower part consists of grey, argillaceous limestone with poorly preserved brachiopods, collection $C_{1-2}$-F15 (Early to middle Carboniferous); upper part is light grey, granular limestone with round and elliptical concretions; disintegrated remains of productids are rare within the concretions

70 m of **biocalcarenite** and argillaceous **limestone**: massive, grey, crinoidal; foraminifers and brachiopods of collection $C_{1-2}$-F14 (Early to middle Carboniferous) from this succession

20 m of **limestone**: thin bedded, grey, yellow and pinkish, silty limestone.

covered

## $P_{1-2}$ (Lower to Upper Permian) Unit

**$P_{1-2}$ Section 1.** Composite section from the Khishchnikov River area, measured by V.G. Ganelin and A.V. Matveev. Localities 20, 21 (Fig. 2). Lat. 71°03.5′N, long. 179°11′W and lat. 71°03.5′N, long. 179°09′W (illustrated in Fig. 39).

- thrust in covered interval

- approximately 400 m of **slate**: monotonous, black, with a few 3–5 m thick lenticular units of fine to medium grained, pinkish grey, quartz-feldspathic **sandstone** with pyrite concretions (upper member)

- 100 m of **slate/siltstone**: variegated, yellow, orchery; heavily impregnated with fine pyrite and with rare crystals up to 2.5 cm in diameter; at the top of the unit is a thin, platy, grey, granular, foetid **limestone** with a layer of bioclastic debris derived from the bivalve *Kolymia* ($P_{1-2}$–F8, Permian) (upper part of the variegated or middle member)

- 40 m of **limestone**: dark grey, thin bedded, fine to coarse grained, equigranular, interbedded with 1 to 1.5 m thick units of dark grey lime mudstone in the upper part (lower part of the variegated or middle Member)

- 250 m of **argillite-slate and chlorite-sericite slate**: black, green and off-white, monotonous, massive, chloritic, with minor, very thin beds of granule sandstone composed of clasts of altered sandstone, grey chert and crinoid ossicles; pyrite nodules are abundant (lower member)

- overlies the $C_{1-2}$ Unit

**$P_{1-2}$ Section 3.** Basal part measured on the Neizvestnaya River. Locality 19 (Fig. 2). Lat. 71°22′N, long. 179°35′W (illustrated in Fig. 39).

- top not exposed (see section 3A)

- 100 m of **limestone**: dark grey, granular, massive, foetid

- 1.5 m of **limestone**: siliceous, with ghosts of detrital fossil debris, including crinoids and brachiopods (including spiriferoids)

- 3–4 m of **quartz sandstone**: medium to coarse grained, thin to medium bedded, dark grey, yellowish, well indurated

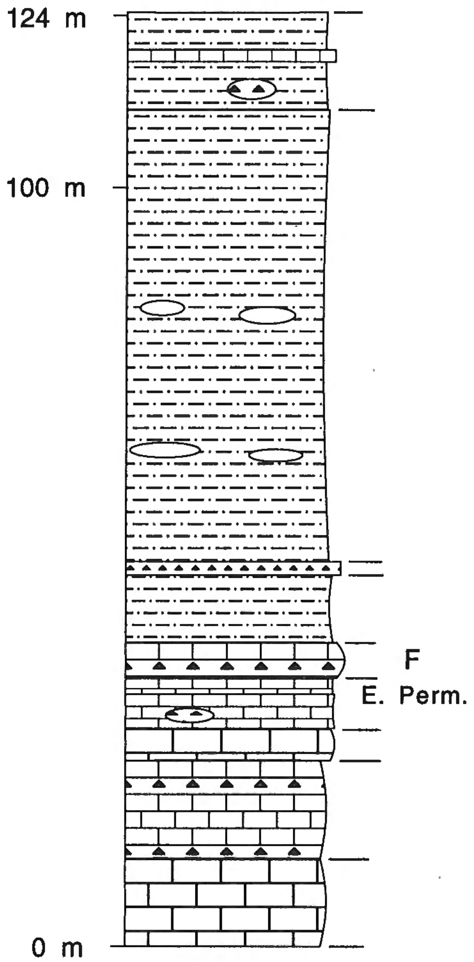
- **FAULT WITH MISSING SECTION**

- approximately 70 m of **limestone**: massive, homogeneous, grey, granular, foetid, with *Kolymia* fragments (as in $P_{1-2}$–F8); locally slaty; foraminifers $P_{1-2}$–F4 (Permian) are from this position

- 160 m thick **breccia**: units composed of blocks and boulders and smaller clasts of various lithologies with almost no matrix; less abundant units of black slate grading into siltstone with suspended blocks of various rock types; the blocks, boulders, and clasts are up to 10 x 2 m in size and consist of limestone, siliceous limestone, argillaceous carbonate, slate, quartzite, vein quartz, schistose basalt, polymictic conglomerate, breccia-conglomerate, and biocalcarenite; one of the limestone blocks contains a single brachiopod specimen, collection $P_{1-2}$–F7 (Late Carboniferous to Permian)

- unconformably overlies $S_2D_1$ Unit limestone

**$P_{1-2}$ Section 2.** Section measured in the area immediately north of Cape Ptichii Bazar through the variegated (middle) member. Locality 18 (Fig. 2). Lat. 71°08.5′N, long. 179°48′E.




upper part of the $P_{1-2}$ Unit, not observed

12–13 m of **slate/siltstone**: variegated, similar to underlying unit, with thick to very thick units of **limestone**: variegated and grey, fine to coarse grained, thin bedded and some beds of green argillite; abundant pyrite with euhedral crystals up to 3 cm, lenses of chert; limestone is locally slump folded

60 m of **slate/siltstone**: variegated, in alternating medium to thick beds of green, pink, grey, yellow, orange and red; a large number of thin and some thick beds, made up of 60 % rhodochrosite concretions, are found throughout the succession

1.5 m of **chert**: thin bedded, argillaceous, with argillaceous chert concretions that vary from 3 to 15 cm

8.5 m **argillite**: dark grey; massive in the lower part, but the upper part is thin bedded, with alternating red and black colours; minor slump folds

5 m of **limestone**: granular, grey, with dark grey chert interbeds; Early Permian foraminifers, collection $P_{1-2}$-F2

2.5 m of **limestone**: grey, granular, massive to thin bedded

6 m of **limestone**: massive and flaggy, siliceous, with lenses of dark grey chert

3.5 m of **limestone**: dark grey, massive, thick and thin bedded

10–12 m of **limestone**: grey, granular, with medium to thick interbeds of replacement **chert** and dark grey chert; Early Permian foraminifers, collection $P_{1-2}$-F1

10–12 m of **limestone**: foetid, grey, granular

overlies the basal slate and clastic part of the $P_{1-2}$ Unit

**$P_{1-2}$ Section 4.** Section measured through the variegated (middle); Tundrovaya River near $P_{1-2}$ Section 3. Locality 22 (Fig. 2). Lat. 71°19.5′N, long. 179°52′W.

- top not exposed
- 100–150 m of **limestone**: light grey, granular, foetid, with coquina beds containing gastropods, brachiopods and *Kolymia* ($P_{1-2}$–F3); foraminifers were also discovered from other beds, collection $P_{1-2}$–F3 (Late Permian)
- bottom not exposed

**$P_{1-2}$ Section 5.** Section measured in the upper part of the unit, east bank of the middle Neizvestnaya River. Locality 23 (Fig. 2). Lat. 71°21′N, long. 179°32′W (illustrated in Fig. 39).

- top eroded
- approximately 150 m of **slate**: black
- 30 m of **sandstone**: polymictic, medium to coarse grained, poorly sorted and with some grit, passing upward into pebbly **gritstone** and arenaceous **limestone**; gritstone grains and pebbles are quartz, chert, and slate; limestone occurs as lenticular coquina beds up to 1.5–2 m thick with brachiopods and foraminifers, collection $P_{1-2}$–F5 (Late Permian)
- 70 m **slate**: black
- 40 m of **slate**: black, with 2–3 m thick units of **limestone**: grey, foetid, foliated
- 10 m of **limestone**: light grey, foliated, foetid
- 25 m of **slate**: black
- 5 m of **limestone**: light grey, foetid
- 100 m of **slate**: black
- 30 m of **limestone**: light grey, flaggy, foetid, laminated
- 60 m of **slate**: black
- 20 m of **chert**: massive
- 60 m of **slate**: black
- 25 m of **sandstone and gritstone**: calcareous, polymictic, with limestone beds; crinoid columnals and fragments of brachiopods, collection $P_{1-2}$–F6 (Carboniferous to Permian)
- approximately 15–20 m of **slate** and **chert**: interbedded, black slate
- 20 m of **limestone**: microcrystalline, grey, foetid as in limestone unit below
- 5 m of **slate**: black
- 10 m of **limestone**: microcrystalline, grey, foetid
- 15 m of **limestone**: foetid, alternating grey, pinkish, or cream coloured, thin bedded, microcrystalline, with laminae of black, slaty limestone
- 15 m of **slate**: black
- 15 m of **limestone**: thin bedded, laminated, grey, pink and cream, microcrystalline, foetid
- approximately 10 m of **slate**: black
- not observed but believed to correlate with the top of $P_{1-2}$ Unit Section 3

## APPENDIX 3

### Geochemical composition of Wrangel Complex rocks

[All analyses by XRF except FeO, $H_2OT$, $CO_2T$, C and S, which were analyzed by rapid chemical methods. $Fe_2O_3$ calculated using $Fe_2O_3$ = $Fe_2O_3$ (XRF) - 1.111134*FeO (volumetric)]

| **Major elements (%)** | **HBB-86-3** | **HBB-86-4** | **HBB-86-8** | **HBB-86-5** | **HBB-86-20.5b** | **HBB-86-20.7** | **HBB-86-20.8b** |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 47.3 | 66.1 | 76.5 | 73.9 | 43.6 | 72.0 | 48.4 |
| $TiO_2$ | 1.23 | 0.72 | 0.14 | 0.05 | 2.42 | 0.46 | 2.86 |
| $Al_2O_3$ | 6.4 | 15.4 | 12.6 | 14.4 | 13.2 | 10.6 | 15.0 |
| $Cr_2O_3$ | 0.24 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| $Fe_2O_3T$ | 6.3 | 4.4 | 1.5 | 0.5 | 12.5 | 3.1 | 12.9 |
| $Fe_2O_3$ | 1.1 | 1.7 | 0.4 | 0.1 | 3.8 | 0.9 | 4.7 |
| FeO | 4.7 | 2.5 | 1.0 | 0.4 | 7.8 | 2.0 | 7.4 |
| MnO | 0.10 | 0.07 | 0.01 | 0.02 | 0.43 | 0.14 | 0.31 |
| MgO | 9.00 | 1.66 | 0.16 | 0.14 | 6.67 | 1.10 | 4.91 |
| CaO | 17.64 | 1.47 | 0.50 | 0.82 | 8.17 | 3.68 | 6.86 |
| $Na_2O$ | 2.2 | 2.7 | 2.8 | 3.5 | 2.1 | 2.5 | 4.8 |
| $K_2O$ | 0.06 | 3.74 | 5.66 | 4.63 | 1.06 | 2.30 | 0.78 |
| $H_2OT$ | 1.6 | 2.4 | 0.6 | 1.0 | 4.7 | 1.4 | 2.8 |
| $CO_2T$ | 7.2 | 1.0 | 0.3 | 0.5 | 6.5 | 2.9 | 0.2 |
| $P_2O_5$ | 0.13 | 0.17 | 0.00 | 0.20 | 0.22 | 0.07 | 1.79 |
| S | 0.05 | 0.00 | 0.01 | 0.00 | 0.01 | 0.04 | 0.01 |
| Total (%) | 99.1 | 99.8 | 100.6 | 99.7 | 100.8 | 100.2 | 100.9 |
| **Minor elements (ppm)** | | | | | | | |
| Ba | 361 | 1104 | 188 | 157 | 260 | 388 | 306 |
| Nb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rb | 0 | 110 | 183 | 156 | 80 | 79 | 28 |
| Sr | 140 | 136 | 67 | 82 | 135 | 179 | 286 |
| Y | 0 | 31 | 25 | 0 | 3 | 41 | 41 |
| Zr | 61 | 337 | 150 | 56 | 94 | 153 | 209 |

HBB-86-3 - foliated porphyritic granite sill, lat. 71°07′N, long. 179°14′W
HBB-86-4 - quartz-potassium-muscovite leucogranite, lat. 71°05′N, long. 179°13′W
HBB-86-8 - acidic volcanic flow or subvolcanic sill, lat. 71°05′N, long. 179°13′W
HBB-86-5 - muscovitic leucogranite, lat. 71°05′N, long. 179°13′W
HBB-86-20.5B - chlorite-carbonate schist, lat. 71°05′N, long. 179°13′W
HBB-86-20.7 - acid to intermediate crystal tuff, lat. 71°05′N, long. 179°13′W
HBB-86-20.8b - gabbro, lat. 71°05′N, long. 179°13′W