THE USE OF SATELLITE SYNTHETIC APERTURE RADAR TO IDENTIFY, CLASSIFY, AND CORRELATE GLACIAL MORAINES IN CHUKOTKA, RUSSIA

P.A. Heiser, J.J. Roush (Department of Geology and Geophysics and the Geophysical Institute, University of Alaska, Fairbanks, AK 99775)

ABSTRACT

The current paradigm for Late Wisconsin (18,000-20,000 BP) glaciation in Beringia calls for limited ice expansion that left the Bering Shelf exposed and available for the dispersal of ice age biota between Asia and North America. This model of limited glaciation is supported by field studies of glacial geology, ocean sediments, paleontology, and palynology in both Alaska and Russia. Conversely, a model of *extensive* Late Wisconsin glaciation, based primarily on glaciological modeling, suggests large ice sheets and ice shelves occupied the Bering Strait region during Late Wisconsin time. Using satellite Synthetic Aperture Radar (SAR) we are able to identify many glacial features on the Russian landscape that were previously unobservable by any scientists outside Russian institutes. Measurements from SAR imagery provides information on glacial extent, moraine morphology, and non-sedimentary glacial features such as valley morphology and cirque orientation. Moraine sequences in several areas of Chukotka and the Anadyr region evidence multiple Pleistocene glacial events. By conducting comparative studies on moraines of *known* age in Alaska, we are able to estimate the relative ages of moraines in Russia. Our study of these images suggests that the last major glaciation (presumably Late Wisconsin) was less extensive than older Pleistocene events, whose marks remain on the landscape beyond the younger moraines.

INTRODUCTION

The determination of Pleistocene glacial limits on a global scale has been a major goal in the investigation of ice ages and climate change. Many Quaternary climate reconstructions rely on the extent and timing of paleoglaciers and ice sheets in order to estimate climatic boundary conditions and paleography. In populated areas such as North America and Europe, glacial landforms and stratigraphy have been studied extensively and the timing and extent of Pleistocene glacial events is relatively well understood. Correlations between regions and even between continents have assisted the ongoing investigations of global climate change and its causes. Political and geographic isolation has limited the extent of our knowledge about glacial history in certain parts of the world. The Russian Far East and Alaska, for example, inhabit similar environments and probably contain similar records of climate change through the Pleistocene. Correlations of glacial history across the Bering Strait, however, have been hampered by political and logistical obstacles, as well as by fundamental differences in scientific methodologies and technology between two nations.

Beringia is a broad region bounded on the west by the Kolyma River in Russia and on the east by the MacKenzie River in Canada. The region is divided by the Bering Strait, a presently narrow and shallow seaway between the Pacific and Arctic Ocean. During past ice ages, the build up of continental ice sheets lowered global sea level and exposed the shallow continental shelf of the Bering and Chukchi Seas. This Ice Age land connection between northeast Asia and North America is called the Bering Land Bridge. Since the Land Bridge was emergent only during glacial periods, the timing and extent of glaciation in this region are important controls on the migrations of plants, animals, and early humans between Asia and North America (Hopkins et al 1982).

Research on the Alaskan side of Bering Strait has shown that the climate in northwest and interior Alaska during the Late Wisconsin (14,000-25,000 BP) was cold and dry (Anderson et. al. 1994, Ager 1982). Glacier advances were limited and restricted to the mountainous regions in interior and northwest Alaska (Hamilton et al. 1986, Hamilton 1994). Most Russian field geologists who have worked in Beringia consider the Sartan glaciation in Chukotka to be correlative with the limited ice advances recorded in Alaska during the last ice age (Ivanov 1986, Glushkova pers. comm. 1994). Bespalyy (1984) states that the Sartan glaciation in Chukotka never reached the foothills and that cirque and valley glaciers extended only about 25 kilometers from cirque headwalls. However, an alternative model based on theory and ice sheet modeling rather than field data, calls for extensive glaciation of the Bering Shelf during Late Wisconsin time. This Maximum, or Grosswald Model of Beringian LGM glaciation features a fringe of marine-based ice domes along the southern continental shelf of central Beringia which, together with mountain glaciers expanding onto the continental shelves along the Alaska Peninsula, Koryak Mountains, and Kamchatka, fed a vast ice shelf that flowed southward across the Bering Sea. Mountain-glacier complexes in Alaska were of limited extent, in agreement with field data, but in Chukotka formed a mountain ice cap confluent with an ice sheet located on the continental shelf of the Arctic (Grossvald

1988, Hughes and Hughes 1994). This model has been modified slightly by Hughes and Hughes (1994) to accommodate new data from St. Lawrence Island (Heiser et. al. 1992, Brigham-Grette et. al. 1992).

The first step in testing any model of glaciation is to map glacial landforms such as terminal moraines which delineate the extent of ancient glaciers. Typically, glacial maps are produced by first using topographic maps and airphotos to identify and locate glaciogenic features. Preliminary map work is then followed by field investigation to determine stratigraphic and age relationships. Because the Bering Land Bridge is part of both Russia and the United States, there is considerable difference in the form and degree of available map and airphoto coverage on the two continents. In Russia, maps are of too large a scale to be useful to glacial mapping, airphoto coverage is incomplete and photos are not available outside of the research institutes. While some glacial geologic work has been done on the Russian side, methods and materials vary to such a degree that comparison with the work of American scientists is often difficult. In addition, conflicting conclusions among Russian investigators (e.g. Petrov 1966, Ivanov 1986) prevent an easy evaluation of glacial histories in the region using the existing literature.

For these reasons, it is necessary to find alternative methods for investigating the glacial landforms of Chukotka. Satellite synthetic aperture radar (SAR) imagery may prove useful in the mapping, and possibly in the relative age estimation of moraines. This study is a summary and evaluation of the techniques used so far to investigate glacial landforms using synthetic aperture radar imagery. If successful, the remote sensing of glacial landforms in Russia will provide a useful tool for preliminary glacial mapping, as well as provide an essential base on which to build future projects and investigations. Our preliminary results, presented here, may also shed some light on the debate of limited versus extensive Late Wisconsin glaciation in Chukotka.

For this study, we selected images that show distinct glacial landforms in several locations in Chukotka and Alaska. The areas we have chosen are broadly comparable in latitude, climate, vegetation, and topography. The locations of the images included in this investigation are shown in Figure 1.

METHODS

Synthetic Aperture Radar (SAR) is a high resolution, active microwave sensor that can image the earth's surface regardless of daylight or weather conditions (Curlander and McDonough 1991). SAR coverage is presently available from the European First Earth Resources Satellite (ERS-1) of the European Space Agency. The data from ERS-1 is received and processed into imagery at the Alaska SAR Facility at the Geophysical Institute of the University of Alaska in Fairbanks.

The investigation of landforms in SAR imagery is, to an extent, analogous to the technique of aerial photo analysis. In both types of imagery, qualitative interpretations can be made by visual inspection. In contrast to aerial photography, however, a SAR image is recorded as digital information. SAR data can therefore be analyzed statistically in order to make determinations about the nature of the surface being imaged. Both visual inspection and statistical analysis have been employed in this study.

Visual analysis of glaciated land-scape using SAR involves the identification and description of those geomorphic features within an image that appear to have been deposited or formed by glaciers. Arcuate, linear features bounded by or located at the mouths of wide mountain valleys are interpreted as terminal moraines.

Often a series of moraines is seen emanating from the same valley. Other easily identifiable glacial-geomorphic features in-clude kettles, lateral moraines, drumlins, and eskers. In order for a feature to be resolved it must be large enough to cross through at least two pixels, which has the effect of distinguishing the feature from the surrounding area of otherwise random pixel brightness values (Olmstead 1993). All large scale features can be resolved in SAR imagery which has a pixel size of 12.5 meters and a resolution of 25 m. The dimension of a feature can be determined by measuring the number of pixels that compose the feature and calculating a distance or an area based on the 12.5 m pixel size.

It is important to point out that SAR images contain a number of significant geometric distortions which can complicate the location and measurement of features. Terrain is severely distorted due to the ERS-1 satellite "look angle" which is inclined 23 degrees from vertical (Curlander and McDonough 1991). This has the effect of causing extreme topography to 'lean' toward the satellite. Image data within the fore-slopes and backslopes of steep mountains, for example, will be lost. This is not a significant problem, however, when obser-ving glacial landforms in wide valleys with relatively flat floors. The topographic relief of moraines is too small to cause significant distortion, but is enough to make the feature identifiable. Another distortion is related to the velocity of the satellite and how that differs relative to different points in the image. This velocity difference effect causes the image area to be warped rather than perfectly square (Olmstead 1993). The effect is less pronounced than the terrain distortion and is not considered a significant source of error. All images are calibrated to filter out random noise so that each image used for analysis is composed primarily of the reflected radar signal.

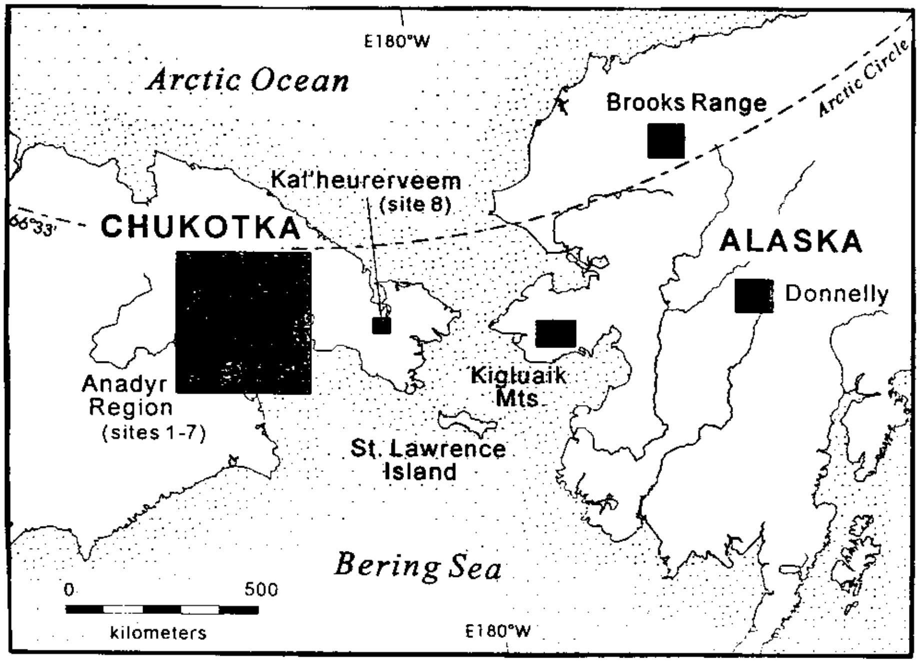

Fig. 1. Map of study area and locations mentioned in the text.

SLOPE ANGLE MEASUREMENTS

The digital data, comprising the image, can be analyzed statistically in order to determine the surface slope angle of landforms in the image. The surface relief of glacial landforms is reduced or 'flattened', over time, by geomorphic agents such as gravity, water, and wind. The relative degree of geomorphic degradation has been used extensively as an estimate of relative age for glacial landforms, especially moraines (Hamilton 1986, Kaufman 1988). Younger features tend to express 'fresh' morphology while older one are more subdued and degraded. Although many factors may influence the morphologic character of a moraine, most workers in glacial geology find that moraine morphology is highly dependent on relative age (Kaufman 1988). An important criteria used in morphologic dependent relative age studies of terminal moraines is slope angle.

The surface slope of a moraine can be determined from a SAR image by measuring the average pixel brightness value for the sloping surface (S. Li, pers. comm. 1994). Each pixel in an image has a numerical '*dn*' value that represents 'brightness' or amount of energy returned to the satellite, and ranges from zero (no return) to 255 (maximum return). This value is a grey scale analog used to represent the *dB* value that expresses the actual signal return to the satellite. The *dB* value is function of the density and electrical properties of the ground surface, the ground surface roughness, and the surface slope angle relative to the incident radar wave. Assuming the first two parameters remain generally constant over the width of the moraine, the brightness of the moraine can be attributed to its surface slope relative to that of the surrounding terrain.

The average brightness value for a moraine slope, or the surrounding terrain, is measured by drawing a box around the area of interest, then recording the brightness values for each pixel inside the box (Figure 2), and averaging the values. The difference in intensity of return between the slope and a nearby flat surface (ΔdB) is used to determine the slope angle. Where:

$$\Delta dB = (dn_s - dn_g) \times 0.1$$

dn_s = average backscatter value of moraine slope
dn_g = average backscatter value of nearby flat surface (background)

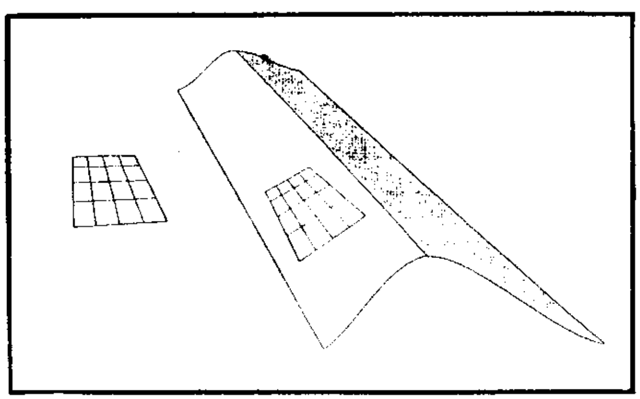

Fig. 2. Idealized illustration of how numerical pixel values are measured from SAR images of glacial moraines.

Local incidence angle (γ) is determined using ΔdB in the following equation (S.Li pers comm. 1994):

$$10\log_{10}\left[\frac{\cos^2(\gamma)/\sin^2(\gamma)}{\cos^2(\Theta)/\sin^2(\Theta)}\right] = \Delta dB$$

The surface slope angle is calculated by subtracting the local incidence angle (γ) from the look angle (θ) of the satellite where the latter is always approximately 23° (Figure 3).

Relative age estimates for several Russian moraines were made by comparing slope angles measured from SAR images to field-measured slope angles on moraines of known age in similar environments in Alaska. Field-measured slope angles were obtained from the literature (Hamilton 1986, Kaufman 1988) or measured using stadial rods and hand held clinometers to determine slope from base to crest of a moraine (Figure 4).

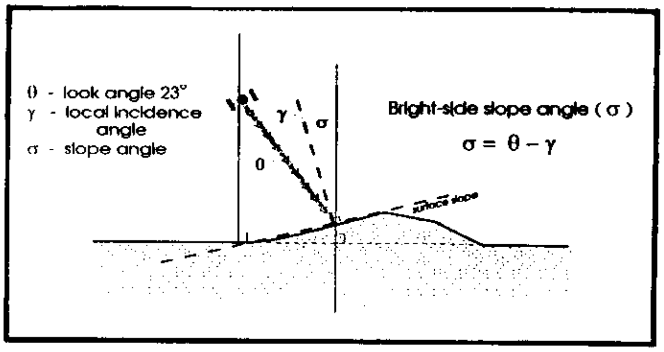

Fig. 3. Geometric relationships used to determine surface slope angles on glacial moraines.

RESULTS

Accuracy of SAR for measuring moraine slopes

The first step in this project was to test the accuracy of slope angle measurements made from satellite SAR. We chose a moraine in the Alaska Range near Delta Junction. The Donnelly moraine is a Late Wisconsin moraine (Péwé and Reger 1989) formed by a glacier that flowed north from the Alaska Range.

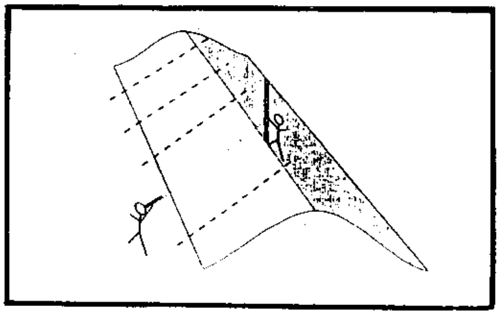

Fig. 4. Illustration of method for measuring moraine slope angles in the field.

In the field, we measured surface slope on eight closely spaced transects along the flank of this moraine and obtained slope angles that ranged from 8 to 25 degrees. In several places there was a break in slope, with the upper portion being steeper, so we made two measurements. The average of all ten measurements is 16.6°. The slope angle measured from SAR was 16.5°. Although this accuracy was unexpected and may represent ideal conditions (SAR images were measured in the exact places field measurements were taken), we believe that SAR-measured slope angles probably are accurate within a few degrees.

We also tested the accuracy of SAR measured slope angles on moraines in the Brooks range by comparing SAR measurements with those made in the field by T.D. Hamilton (1986) . Our measurements of the Itkillik II moraine in the Anaktuvuk Valley indicated slope angles of 21° that compare with Hamilton's field measured angles of 18-23°. Although not measured in precisely the same locations measured on the ground by Hamilton, our results show that SAR slope measurements, taken from a unit area on the flank of a moraine, come close to field measurements taken at specific point locations.

Russian Moraines

In this study we were able to visually identify many glacial features, and mapped approximately fifteen glacial moraines from SAR images of several general locations in Chukotka. We were able to obtain slope angle measurements from seven of the terminal moraines. In this report we will describe glacial features (mostly terminal moraines) from 8 sites (see Figures 1 and 5). Most of the features discussed here are located in the Anadyr River basin of Chukotka (Figure 5).

At the mouth of the Bolshoya Osinovaya River valley (site 1, Figure 5), there are two moraines visible in SAR imagery. An outer moraine is visible as a discontinuous arc that is bounded by and diverts the Yurumkuveyem River. Approximately 15 kilometers upstream on the Big Osinovaya River another, more distinctive, moraine arcs across the mouth of the valley. Each of these moraines forms an arc that is approximately 20 km across, and they are located 150 to 200 kilometers from their probable source area. The inner moraine exhibits greater contrast on the SAR image and is therefore more visible. The crest is also more continuous and easier to distinguish. Some consequent drainage has formed on the inner moraine. The surface slope angle measured on the inner moraine is 12°. The outer moraine is strongly dissected by first and second order drainage systems. The outer moraine, although visible, did not exhibit enough contrast to measure slope angles.

The Pekul'ney Mountains east of the Belaya River valley contain at least two well defined moraines that mark where small glaciers exited the valleys on both sides of the range. Site 2 (Figure 5) is located on the west side of the range and site 3 (Figure 5) is located on the east side. The moraine on the west side, which arcs across

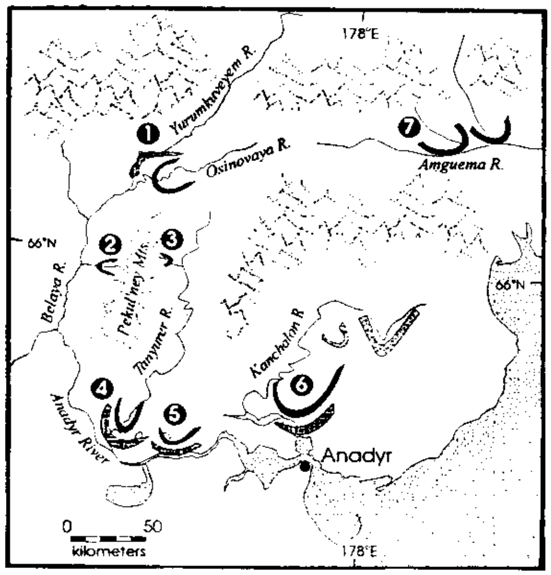

Fig. 5. Location of moraines mapped and described from the Anadyr region, Chukotka.

the Buchia River, is about 8 kilometers across and 35 kilometers from the divide. The moraine on the east side is smaller, 3 - 4 kilometers across and 20 kilometers from the divide. Both moraines show high contrast and continuous crests. There has been relatively little consequent stream development on either of these moraines.

At site 4 (Figure 5) another pair of moraines is dissected by the Tanyurer River (64°45'N, 174°E). An inner moraine, approximately 20 km across the arc, crosses the Tanyurer River about 20 kilometers upstream from its confluence with the Anadyr River. A larger but parallel moraine (50 km across the arc) borders the floodplain of the Anadyr. Both moraines are 150 to 200 kilometers from their probable source area, the mountain range south of the Amguema River. As before, the inner moraine is much more distinctive than the outer one with clear, sharp contrast and a continuous crest. Limited first order stream development is observed on the flanks. Slope angle was measured on the inner moraine and was determined to be 13°. The outer moraine, approximately 10 kilometers beyond the inner one, is hard to discern on the images as it is highly degraded and dissected by drainage gullies and channels. A continuous crest is not visible.

Just to the east (site 5) Melkoy Lake is dammed by a clearly defined moraine. As at sites 1 and 4, this moraine is accompanied by another, older, less distinctive moraine that is parallel but approximately 10 kilometers downstream from the inner one (Figure 5).

The inner moraine is approximately 30 kilometers across and the outer one is about twice that width. Like the other pairs, this set of moraines is approximately 150-200 kilometers from a mountainous source area. The inner moraine is well defined and clearly visible. The crest is uniform and nearly continuous. Small drainage gullies have developed on its flanks. The outer moraine is less clearly defined and exhibits less contrast with the background. The crest is vague and discontinuous along its length. Well-developed drainage patterns are visible over its entire surface and, in places, it is completely dissected by drainage gullies (Figure 6). The slope angle measured on the inner moraine is 10° and the surface slope angle of the outer moraine is 5.5°.

Fig. 6. Pair of moraines at site 5, near Melkoy Lake. White arrows mark areas where slope angle measurements were taken.

The Kanchalon Liman (Estuary) is bounded on the north by another pair of moraines (site 6) like the ones described at sites 4 and 5. Again, the outer moraine is more degraded in appearance and is ~ 10 kilometers beyond the inner one. The slope angle measured on the inner moraine is 9°.

The broad Kanchalon River valley, north of the estuary, contains additional moraines. One of these diverts the Kanchalon river southward along its V shaped form (Figure 5). These moraines are numerous, characterized by abundant kettles and subsequent thaw-pond development.

Approximately 260 kilometers NNE of the city of Anadyr are two very distinctive, high-contrast moraines deposited by ice that pushed into the Amguema River Valley from the north. These moraines form arcuate, high ridges at the mouth of the Vulvyveyem and Irvynetyveyem valleys. These moraines are located approximately 50 kilometers from the valley heads in the mountains from which they originated. The moraines are very fresh looking and have limited drainage patterns developed on them. The measured surface slope on these moraines is 15°.

Further east, series of lobate moraines, approximately 20 km across, evidence glaciers that flowed north out of an unnamed, broad, U-shaped valley draining near the headwaters of the Kalhuerveem River (66°N, 175°E). These moraines are fresh in appearance and exhibit high contrast to the surrounding landscape. The average slope angle measured on these moraines is 16°. They extend approximately 40 kilometers from a likely source area near the Erguveyem valley.

DISCUSSION

Our results indicate that glacial moraines can be identified, and that certain morphologic characteristics can be measured, from SAR images. We are able to classify moraines based on morphology and extent. The data extracted from slope angle measurements and paleo-glacier extent, or approximate distance from source area, enable us to distinguish at least two distinct groups of moraines.

One group of moraines, such as those in the Amguema, and Kalhuerveyem valleys and those in the Pekul'ney mountains possess steep surface slopes (> 15°) and are relatively limited in extent (25-50 kilometers from source). A contrasting group of moraines, which form the outer most arc in the pairs of moraines at Osinovaya (site 1), Tanyurer (site 4), Melkoy (site 5), and Kanchalon (site 6), are much more extensive and degraded in appearance than all the other moraines. They are characterized by shallow slopes (< 5°) and extend up to 200 kilometers from any mountain source area. A third group of glacial moraines form the inner set of moraine pairs at the previously mentioned localities. The inner moraines exhibit intermediate morphology and degradation, and are slightly less in extent than the subdued outer moraines. The slope angles on these intermediate moraines are 9-13°, much steeper than their partners which extend only 10 kilometers further down-valley. Several moraines, upstream in the Kanchalon valley, lack distinctive crests and host numerous kettles and may, therefore, represent recessional moraines and a downwasting ice margin.

By applying our knowledge of the relationship between moraine morphologic characteristics and relative age in similar environments in Alaska (Hamilton et. al. 1986, Kaufman and Calkin 1988) we can make rough age estimates for the moraines in Chukotka. Comparison suggests that the 'fresh', steep (≥15°), proximal moraines at Amguema, Kalhuerveem, and Pekul'ney are correlative with the Mt. Osborne moraines on the Seward Peninsula and the Itkillik II in the Brooks Range. These moraines are considered to be Late Wisconsin in age (Hamilton et. al. 1986, Kaufman and Calkin 1988, Hamilton 1994). Similarly, the low slope angles and large extent of the outer moraines are correlative with the morphology and extent of Nome River and Sagavinirktok moraines in the Kigluaik mountains and Brooks Range, respectively. These moraines are assigned to the Middle Pleistocene by Kaufman and Calkin (1988), Kaufman et. al. (1991) and Hamilton (1986). A glaciation of this age is recorded in the stratigraphy on St. Lawrence Island, and is considered to have originated in the mountains of Chukotka (Benson et. al. 1994, Heiser et. al. 1992). Although there are no preserved moraines on St. Lawrence Island, this glacial event is comparable in relative extent to the one marked by the outer moraines in the Anadyr region.

The intermediate moraines are more difficult to compare with moraines on the Alaskan side of Bering Strait. Several advances are recorded in Alaska between the Middle Pleistocene and the Late Wisconsin. The most distinctive of these in Alaska are the Salmon Lake moraines of the Kigluaik Mountains (Kaufman and Calkin 1988, Kaufman and Hopkins 1986) and moraines of Itkillik I age in the Brooks range (Hamilton 1986), both of which are presumed to be Early Wisconsin in age. St.Larewnce Island also records a second glacial advance that encroached on the island from the northwest. This event occurred sometime after the Last Interglacial period, 125,000 years BP (Heiser et al. 1992, Benson 1994.). The record on St. Lawrence island indicates an older glaciation (Mid Pleistocene) followed by a second advance, nearly as extensive, that dates to less than 125,000 years ago. There is no evidence of any, non-local, Late Wisconsin glaciation on St. Lawrence Island.

The age assignments of Russian workers, agree, in general, with our estimates. The smaller moraines in the Pekul'ney mountains are considered to be Sartan (Late Wisconsin) age (Glushkova pers. comm. 1994) The inner moraines in the Anadyr lowland are considered Zyran (Early Wisconsin) by Glushkova (1992).

The model of extensive ice sheet growth in Beringia during the Late Wisconsin (Grossvald 1988, Hughes and Hughes 1994) is not evidenced by the moraines observed on the Chukotkan landscape. If all the moraines described here were deposited during the recession of extensive Late Wisconsin age ice sheets (as suggested by Hughes, pers. comm. 1994) they should all reflect very similar morphologic characteristics (steep slope, high contrast, fresh appearance, etc.). Instead, the moraines observed in SAR images exhibit dramatic differences in degree of weathering and degradation that corresponds well with position (fresher upstream, subdued downstream). The sequences of moraines in Chukotka are correlative, in morphology and position, with moraine sequences described in Alaska, and therefore appear to evidence a sequence of glacial events which most likely began in the middle Pleistocene and ended with the Late Wisconsin. Continued work on the quantification of morphologic characteristic such as roughness, will help with the estimation of relative ages.

CONCLUSIONS

Satellite synthetic aperture radar imagery shows great promise as a reconnaissance tool for glacial mapping and moraine morphological investigations in regions of the world that have little or no aerial photo or small-scale map coverage. The use of SAR images during the preliminary stage of any research effort in these areas is essential as it provides visual and digital information not otherwise available to aid in making preliminary age determinations and morphologic characterizations.

Our work, so far, suggests that at least two advances of alpine glaciers and mountain ice caps in Chukotka are correlative with advances recorded in Alaska. A glacial event of limited extent, characterized by 'fresh' moraine morphologies with steep slope angles, is comparable in appearance and morphology to Late Wisconsin aged moraines in Alaska. A more extensive glacial limit, marked by low angle degraded moraines, is probably correlative with the middle Pleistocene age moraines described from The Seward Peninsula and the Brooks Range. The general sequence of two similarly extensive events followed by an advance of limited extent is correlative with the glacial record on the Alaskan mainland and on St. Lawrence Island. The presence of these moraine sequences, within the limits of the extensive Late Wisconsin ice sheet proposed by Grossvald, makes such an ice sheet unlikely at that time.

ACKNOWLEDGEMENTS

This study is part of the first collaborative Russian-American investigation of Cenozoic History of Bering Strait Region. Support for this research was provided by the National Science Foundation Grant OPP -9015496. SAR data and image products were provided through a grant from the European Space Agency to David M. Hokins. SAR images were acquired and processed at the Alaska SAR Facility at the Geophysical Institute, University of Alaska Fairbanks. This work has benefited from converstations with Olga Glushkova of Magadan, Russia. Valuable discussion and comments were contibuted by Dave Hopkins and Dan Mann.

REFERENCES

Ager, A., 1982. Vegetational history of western Alaska during the Wisconsin Glacial Interval and the Holocene. - In: D.M.Hopkins, J.Matthews, Jr., C.E.Schweger, S.B.Young, (Eds.) Paleoecology of Beringia. N.Y.: Academic Press: 75-94.

Anderson, P.A., Bartlein, P.J., Brubaker, L.B., 1994. Late Quaternary history of tundra vegetation - In: northwestern Alaska. - Quaternary Res. 41: 306-315.

Benson, S., Brigham-Grette, J., Heiser, P., Hopkins, D., Ivanov, V., Lozhkin, A.V., 1994. Glaciotectonic and geochronologic evidence for early Wisconsin glaciation in Beringia. - Geol. Soc. of Am. Ann. Meeting, Program with Abstracts. October 1994. Seattle, WA.

Bespalyy, V.G., 1984. Late Pleistocene mountain glaciation in northeastern USSR. - In: A.A. Velichko, H.E. Wright, C.W Barsky (Eds.) Late Quaternary Environments of the Soviet Union. Minneapolis: Univ. of Minnesota Press: 31-33.

Brigham-Grette, J., Benson, S., Hopkins, D., Heiser, P., Ivanov, V., and Basilyan, A., 1992. Middle and Late Russian glacial extent in the Bering Strait Region: Results of recent field work. - Geol. Soc. Am. Ann. Meeting Program with Abstracts. Cincinnati, OH.

Curlander, J., and McDough, R. (1991). Synthetic aperture radar systems and signal processing. - N.Y.: John Wiley and Sons.

Glushkova, O.Yu., 1992. Paleogeography of Late Pleistocene glaciation of Northeast Asis. - International Conference on Arctic Marginss September 1992. Anchorage, Alaska. Abstracts: 21.

Glushkova, O.Yu., 1994. Personal communication. - Magadan: NEISRI FEB RAS.

Grosswald, M.G., 1988. An Antarctic-style ice sheet in the Northern hemisphere: toward a new global glacial theory. - Geography and Geol. 12 (4): 239-237.

Hamilton, D., 1994. Late Cenozoic glaciation in Alaska. - In: G.Plafker and H.C. Berg (Eds.) The Geology of Alaska. The Geology of North America G-1. Geol. Soc. of America.

Hamilton, D., 1986. Late Cenozoic Glaciation of the central Brooks Range. - In: D. Hamilton, K.M Reed, R.M.Thorson (Eds.) Glaciation in Alaska - The Geologic Record. Alaska Geol. Soc., Anchorage, AK: 9-49.

Hamilton, D., Reed, K.M, Thorson, R.M. (Eds.), 1986. Glaciation in Alaska - The Geolgic Record. Alaska Soc., Anchorage, AK.

Heiser, P.A., Hopkins, D.M., Brigham-Grette, J., Benson, S.L., Ivanov, V.F., Lozhkin, A.V., 1992. Pleistocene Glacial Geology of St. Lawrence Island, AK. - Geol. Soc. of Am. Ann. Meeting Program with Abstracts. 1992. Cincinnati OH.
Hopkins, D.M.. Matthews, J., Schweger, C.E., Young S.B. (Eds), 1982. Paleoecology of Beringia. - N.Y.: Academic Press: 75-94.
Hughes, B.A. and Hughes, T.J., 1994. Transgressions: rethinking Beringian glaciation. - Palaeogeogr., Palaeoclim., Palaeoecol. 110: 275-294.
Hughes, T.J., 1994. Personal communication. - Oro: Dept. of Geol. Sci., Univ. of Maine.
Ivanov, V.F., 1986. Quaternary Deposits of Coastal Eastern Chukotka. - Vladivostok: DVNTz AN SSSR
Kaufman, D.S., Walter, R.C., Brigham-Grette, J. and Hopkins, D.M., 1991. Middle Pleistocene age of the me River glaciation, northwestern Alaska. - Quaternary Res. 36: 277-293.
Kaufman, D.S., and Calkin, P.E., 1988. Morphometric analysis of Pleistocene glacial deposits - In: the Kigluaik Mountains, northwestern Alaska, USA. - Arctic and Alpine Res., 20 (3): 272-284.
Kaufman, D.S., and Hopkins, D.M., 1986. Glacial History of the Seward Peninsula. - In: D. Hamilton, K.M Reed, R.M.Thorson, (Eds.) Glaciation in Alaska - The Geolic Record. Alaska Geol. Soc., Anchorage, AK: 51-78.
Li, S., 1994. Personal communication. - Fairbanks: Geoph. Inst., Univ. of Alaska.
Olmstead, C., 1993. Alaska SAR Facility Scientific SAR Users Guide. - Fairbanks: Geoph. Inst., Univ. of Alaska,
Petrov, O.M., 1966. Stratigraphy and fauna of marine mollusks in the Quaternary depositions of the Chukchi Peninsula. (English Translation by Lydia A. Hutchinson, Scripps Inst., La Jolla CA). M.: Nauka, 288 p.
Péwé, L., and Reger, R.D., 1989. Middle Tanana Valley. - In: Quaternary Geology and Permafrost along the Richardson and Glenn Highways between Fairbanks and Anchorage, Alaska. 28th Intern. Geol. Congr. Field Trip Guidebook T102: American Geoph. Union: 17-24.