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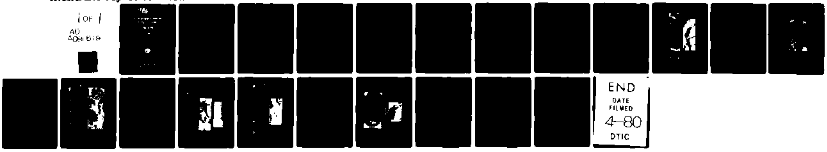
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PASSIVE MICROWAVE SIGNATURES OF SEA ICE FEATURES

FINAL REPORT

R. D. KETCHUM, JR.
A. W. LOHANICK

OCEANOGRAPHY DIVISION

NAVAL OCEANOGRAPHIC LABORATORY

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NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529

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FOREWORD

Arctic environmental studies conducted by the NORDA Polar Oceanography Branch emphasize the support of ASW and sea ice forecasting objectives. The continued evaluation of remotely sensed sea ice data to determine its application to arctic environmental studies and to develop new data collection methodology is considered a primary corollary of this work. The passive microwave imagery analyzed for this report has provided further insight into the distribution of radiometric temperatures in the sea ice environment. Speculation and hypotheses derived from this work and the work of other investigators have shown the need for further airborne and surface observations as well as laboratory investigations. It is known that passive microwave systems and techniques can provide environmental information unavailable from other sensors. Already, existing passive microwave systems have a strong potential for real-time use to shipping and fleet operations in ice covered waters. Improved capabilities will be realized through further system development, environmental testing, and data evaluation.

EXECUTIVE SUMMARY

In April 1976 the NORDA Polar Oceanography Branch conducted airborne experiments over the Chukchi and Beaufort Seas to evaluate sea ice data taken by the Naval Weapons Center, China Lake passive microwave imaging system (MICRAD). The MICRAD system was flown on a C-130 aircraft operated by the 146th Tactical Air Wing, Van Nuys, California. The Naval Oceanographic Office BIRDSEYE P-3A aircraft, equipped with cartographic camera and infrared line scanner, was flown in company with the C-130 so that simultaneous ice coverage could be obtained by all sensors for subsequent correlation and evaluation.

The results of the evaluation have given a good insight into the relative radiometric temperature distributions from a sea ice cover comprised of many different ice forms and features of varying age and thickness, and in various stages of formation, deformation, and weathering. The lowest radiometric temperatures were recorded over open water, some areas of very new ice which presumably had a moist surface, and over some multi-year ice floes and other ice forms which apparently had experienced considerable internal stress. As a result, it has been hypothesized that internal ice structure changes brought about by severe stresses result in a lowered emissivity. The highest radiometric temperatures were displayed by areas of thin ice which presumably no longer sustained a surface moisture, new ice ridges, and some frozen melt ponds. The older, thicker areas of first-year ice appeared to have lower radiometric temperatures than the thinner areas of first year ice. Single multi-year ice floes often displayed a wide radiometric temperature range. This has been attributed to physical property changes which resulted from summer melting and erosional processes, and from stresses produced by the interaction of floes.

It has been suggested that some old ice forms and new ice ridges are low-loss media and are to some significant degree transparent to microwave radiation. The principal radiation from these features may originate at subsurface levels.

The detection of stress fields and/or stress lines through the use of microwave techniques is a new concept developed by the analysis of this MICRAD data. This concept invites further investigation.

LIST OF ILLUSTRATIONS

INTRODUCTION

Navy sea ice research is directed primarily toward support of ASW and sea ice forecasting objectives in the arctic environment. The inaccessible nature of the ice covered Arctic Ocean and its marginal seas, due to their remoteness and perennial ice cover, compounded by long periods of darkness and difficult weather conditions necessitates that data be collected via aircraft and satellite remote sensors. Research studies require much physical data on the basic properties of ice, its formation, growth, deformation, and deterioration; time-space distribution of sea ice/water features with particular reference to the distribution of ridges, ice thickness, and water openings; and the ice dynamics or in specific terms, ice motion, stress-strain relationships, and deformational activity. All of these elements are closely related to and controlled by the environmental atmospheric and oceanographic conditions. A better understanding of the physical processes influencing and controlling the air-ice-sea interactions is essential to the development of prediction models and forecasting techniques needed to support fleet exercises in the arctic environment.

The ability of passive microwave systems to provide useful information under weather conditions unsuitable for visual sensing has attracted considerable interest in the field of sea ice reconnaissance and forecasting. Moreover, the microwave sensors can provide complementary information which is unobtainable through the use of other sensors. How much additional information can be obtained from the use of passive microwave sensors and techniques has become a subject of more recent research.

ARCTIC SEA ICE

The sea ice canopy which perennially covers the Arctic Ocean and its marginal seas is a dynamic body which is in constant motion. Winds and currents are the major elements which influence the ice motion. In some areas of the marginal ice zone, waves and swell may also play an important role. Pressures within the ice fields produce deformational features such as fractures, polynyas (water openings), and ice ridges and hummocks. Fractures can by very narrow or many meters wide and may extend over many kilometers. Ice pressure ridges can reach heights of 10 meters and may have keels reaching depths of 50 meters, although this is rare. Pressure ridges are usually formed from thinner ice types of recent formation in fractures.

There are several basic stages of ice development which are categorized by age and/or thickness. Old ice is sea ice which has survived at least one summer's melt. It can be subcategorized into second-year ice, which has survived only one summer season, and multiyear ice which has survived two or more summer seasons. This ice is characterized by an irregular, undulating topography which has resulted from the summer erosional processes of melting and water runoff. Ridges and hummocks have been smoothed, and drainage and puddle patterns are apparent. A multi-year ice floe may be comprised of many ages of ice and they may be three meters thick or more. First-year ice has several subcategories, but in all cases this ice type represents one season's growth. It can range from 30 cm to 2 m in thickness and has a relatively smooth surface. New ridges and hummocks are common in first-year ice. Earlier stages of ice development include young ice, which is 10-30 cm thick and nilas which is up to 10 cm thick. New ice is a general term for recently formed ice which includes frazil ice, grease ice, slush, and shuga. These types of ice are composed of ice crystals which are only weakly frozen together, and have relatively high salinities.

The physical properties of sea ice are extremely variable and depend on a number of factors such as rate of freezing, salinity of the original sea water, salinity and temperature of the ice, porosity, pressure, crystal structure, and the age of the ice. The interrelationship between ice thickness, water temperature, and air temperature has much to do with altering the properties of a section of ice. However, the most extreme changes are likely to occur during summer thaw when the salinity of the upper layer of the ice is greatly reduced and melt water from surface snow and ice may fill the interstitial cavities. The upper layer may be essentially salt free. The physical properties of sea ice, particularly old ice, can be very inhomogeneous, and its dielectric constant may vary considerably with depth and laterally.

FIELD EXPERIMENT

During the period 28 March - 8 April 1976, the Naval Ocean Research and Development Activity conducted remote sensing flights over the Chukchi and Beaufort Seas. One experiment objective was to evaluate sea ice data collected by the Naval Weapons Center, China Lake passive microwave imaging system (MICRAD). This report describes the results of the MICRAD sea ice data analysis.

Two aircraft were involved in the MICRAD experiment. The Naval Oceanographic Office Project BIRDSEYE P-3A aircraft, equipped with a CA-14 9-inch frame format cartographic camera, an AN/AAR-35 infrared line scanning system, and a laser surface profiling system, was flown in company with a C-130 aircraft from the 146th Tactical Air Wing, Van Nuys, California. The MICRAD system, operated by personnel from the Naval Weapons Center, was mounted in the aft section of the C-130. The rear cargo door was opened during the operation and the system, utilizing a one-degree beam width and a 140 degree scan angle, viewed the ice terrain at an angle of approximately 35 degrees aft of nadir. MICRAD is a K_a band (33.6 GHz) airborne mapping system designed for microwave radiometric measurements of the terrain. It is a system built primarily for the display of radiometric information and not for quantitative measurements of temperature differentials.

Several hundred miles of coincident microwave, photographic, and thermal IR data were obtained at altitudes ranging from 1000 to 9000 feet. These data have been thoroughly cross correlated to improve microwave imagery interpretation techniques and to develop hypotheses which may help explain radiometric temperature differentials as related to sea ice environmental processes, features, and conditions.

RESULTS

The MICRAD data analysis has given a good insight into the general distribution of relative radiometric temperatures from a sea ice cover comprised of many different ice forms and features of varying age and thickness, and in various stages of formation, deformation, and weathering. In addition, based on evidence seen in this analysis, hypotheses have been developed in an attempt to explain some patterns in the sea ice radiometric temperature displays.

"Radiometric temperature" or "brightness temperature" refer to the intensity of radiation received at the wavelength of the radiometer (here, about 9 mm). The radiometric or brightness temperature is a result of the physical temperature of the body, and its ability to radiate its thermal energy towards the antenna (its emissivity). Thus, for two bodies having the same physical temperature, the one with the higher emissivity will have the higher brightness temperature. At present, very little is known about the relationship between the physical properties of a body and its emissivity.

Radiometric signatures of various sea ice types discovered by other investigators [Wilheit et al., 1972; Gloersen et al., 1973; Meeks et al., 1974; Tooma et al., 1975; Campbell et al., 1976] were displayed in the MICRAD imagery. The lowest radiometric temperatures (i.e. brightness temperatures) in the sea ice environment occurred in areas of open water, very recent thin ice which presumably still had a wet surface, and areas of ice which have experienced considerable stress. The highest radiometric temperatures were displayed by the most recently formed areas of ice which presumably no longer sustained a surface moisture, and by frozen melt ponds. As first-season ice becomes older and thicker, it becomes radiometrically cooler, but after it survives one or more summer (melt) seasons its physical properties have been changed significantly by erosion, deformation and other aging processes. The changes in physical properties are manifested by the complex radiometric temperature distribution displayed by many older multi-year ice floes. The MICRAD imagery has indicated that many multi-year ice floes have a spectrum of radiometric temperatures apparently spanning the full range seen in this environment.

These data suggest that some old ice forms and deformed ice features, such as ridges, are low-loss media and to some significant degree are transparent to microwave radiation, and that the principal radiation from these features originates at subsurface levels. The properties of old sea ice, and deformed sea ice which has been forced upwards out of the water, have been drastically changed by aging, weathering, brine drainage and/or leaching. Brine solutions are often replaced by salt free snow and ice melt which refreezes during the winter months. These reconstituted ice forms are believed to be low-loss media (e.g. Vant [1976]) and should be transparent in varying degrees to electromagnetic energy.

Meeks et al. [1974] concluded that at 13.4 GHz (2.2 cm), increasing ice porosity results in a lower brightness temperature, indicating that volume scattering of microwave radiation in the higher-porosity multi-year ice lowers the microwave emission. Vant [1976] has discussed the difficulty in building a dielectric model for multi-year ice since scattering from large air bubbles is very important. Since stresses in the ice should result in some appreciable change in porosity (be it temporary or permanent) a change in emissivity, hence brightness temperature, should be expected. Our data suggest that stresses in sea ice may produce ice crystal deformation and/or change the ice porosity and that this results in lowered radiometric temperatures (i.e., emissivities). This is particularly true in the older ice forms which are less elastic than the young ice forms. If this is so, we ask if elastic ice crystal deformation as well as permanent deformation and/or internal rupturing produces changes in radiometric temperatures.

ILLUSTRATIVE EXAMPLES

In the following examples the lowest radiometric temperatures appear in the lightest gray tones on the MICRAD imagery. It should be noted that a given gray tone does not always represent the same radiometric temperature and that false signals are recorded along some feature boundaries when signals suddenly change at a boundary between targets which have significantly different radiometric temperatures. For example, when scanning from a low radiation feature to a high radiation feature, when the change is large, initially the feature having the higher radiometric temperature will be portrayed as a higher radiator than it actually is. The reverse is true when scanning from a high to a low radiometric temperature.

Annotated feature pointers in the figures end at approximately the same terrain location on the various images shown, and labels such as "MY" on the images, are at approximately the same terrain locations from image to image.

The areas of apparent open water in Figure 1 (left end) are portrayed as very low radiators as expected. So are some of the smaller multi-year ice (MY) floes located within the deformed area of first-year ice (FY) on the left end of the strip. Areas of very new ice or nilas (less than 10 cm thick) such as the fracture on the right end of the strip are relatively low emitters. This is probably due to surface moisture. Areas of young ice 10-30 cm thick, as shown on the fracture near the center of the strip, are relatively high emitters. Areas of first-year ice, such as that shown here, show a brightness temperature between that of the nilas and young ice (YNG) categories. In other words, in the very early stages of development the ice is initially a low emitter due to surface moisture, then subsequently a relatively high emitter; and then emission levels drop to an intensity intermediate to the early variations.

As can be seen in Figure 1, areas of first-year ice are relatively high and homogeneous

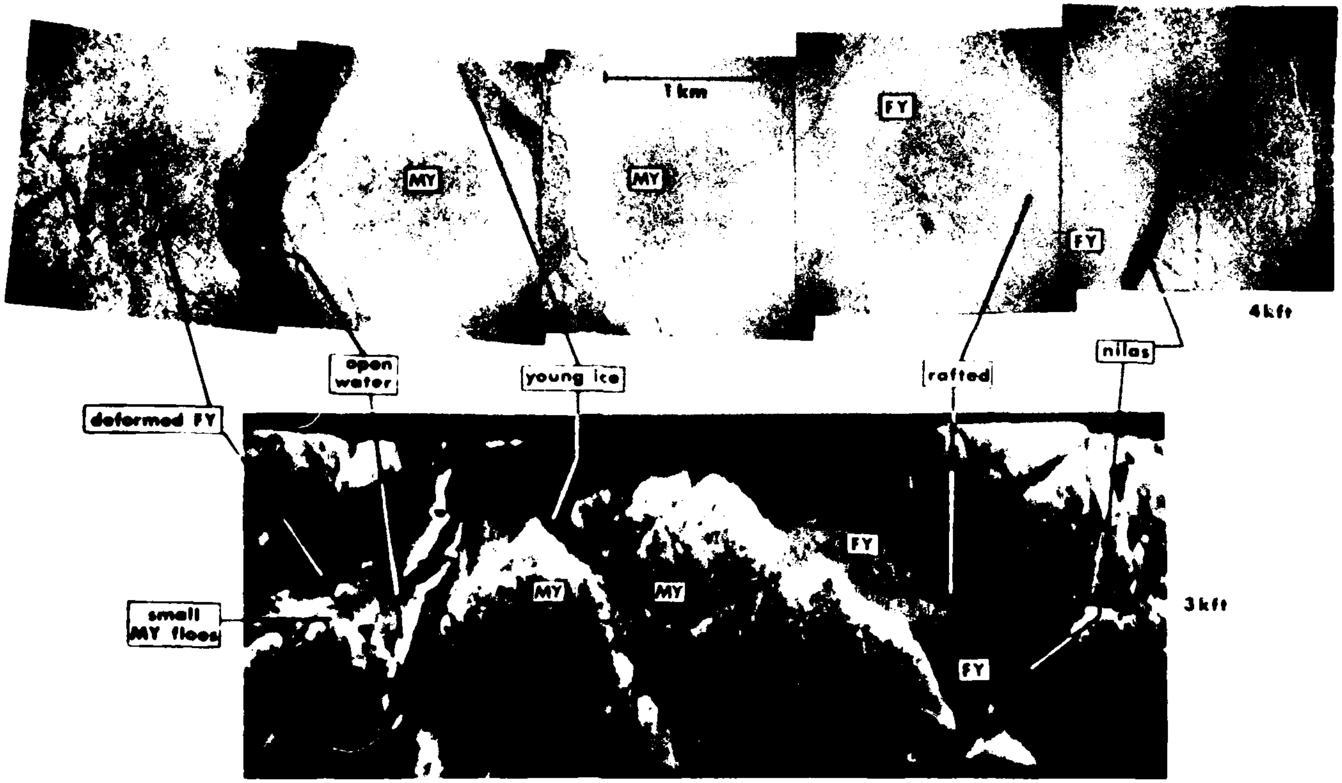

Figure 1. Photographic (top) and MICRAD Images. MICRAD Image Shows a Radiometric Temperature Display of Various Ice Types and Features.

emitters in the sea ice environment. There is no evident distinction on the MICRAD data between ridged areas of first-year ice and the relatively undeformed first-year ice. The ridges in the first-year ice cannot be distinguished from their background. However, rafted ice, some of which is present near the right end of the strip, appears radiometrically cooler than its background of similarly aged, deformed ice. It is speculated that stress which produces rafting may also cause a permanent internal physical structure change which lowers the radiation level in this case.

The above evidence and other similar evidence seen in this analysis indicate that changes which occur in the physical properties of ice during very early growth stages and as a result of deformational processes have a strong impact on the ice radiation characteristics.

Identification and discrimination of multi-year ice can be done easily and accurately on the MICRAD imagery. Multi-year ice, on the average, displays cooler radiometric temperatures than the younger ice types, although a wide spectrum of radiometric temperatures may be present on a single multi-year ice floe. Varying erosion, deformation, and aging processes experienced by the ice comprising a multi-year ice floe should result in the inhomogeneous distribution of physical properties. Thus, older multi-year ice would be expected to have a more complex, diversified distribution of radiometric temperatures. Because of this, multi-year ice images often display a variegated texture. This texture, combined with a generally non-angular, sometimes rounded shape, makes multi-year ice floes easy to identify and delineate.

New ice ridges transecting multi-year ice floes, as can be seen in Figure 1, appear as dark lineations (high emitters), but cannot be confidently distinguished from narrow ice covered fractures in multi-year ice.

The variations in radiometric temperatures of thick first-year ice, thin first-year ice, and rafted ice are very evident in Figure 2. The rafted thin first-year ice, most distinguishable on the thermal IR imagery (in which lighter tones represent high temperatures), is also clearly visible on the MICRAD imagery as a cool radiometric signature against the warmer background thin first-year ice which is the same age. The areas of thick first-year ice on the left end of the imagery and the heavily ridged area of thick first-year ice on the right portion of the imagery also display cooler radiometric temperatures than the thin first-year ice. There is no evidence of the ridges in these areas on the MICRAD imagery.

The ice-covered fractures and the ridge crossing the multi-year ice floe in the upper left corner of the imagery are good examples of the similar appearance of these features on

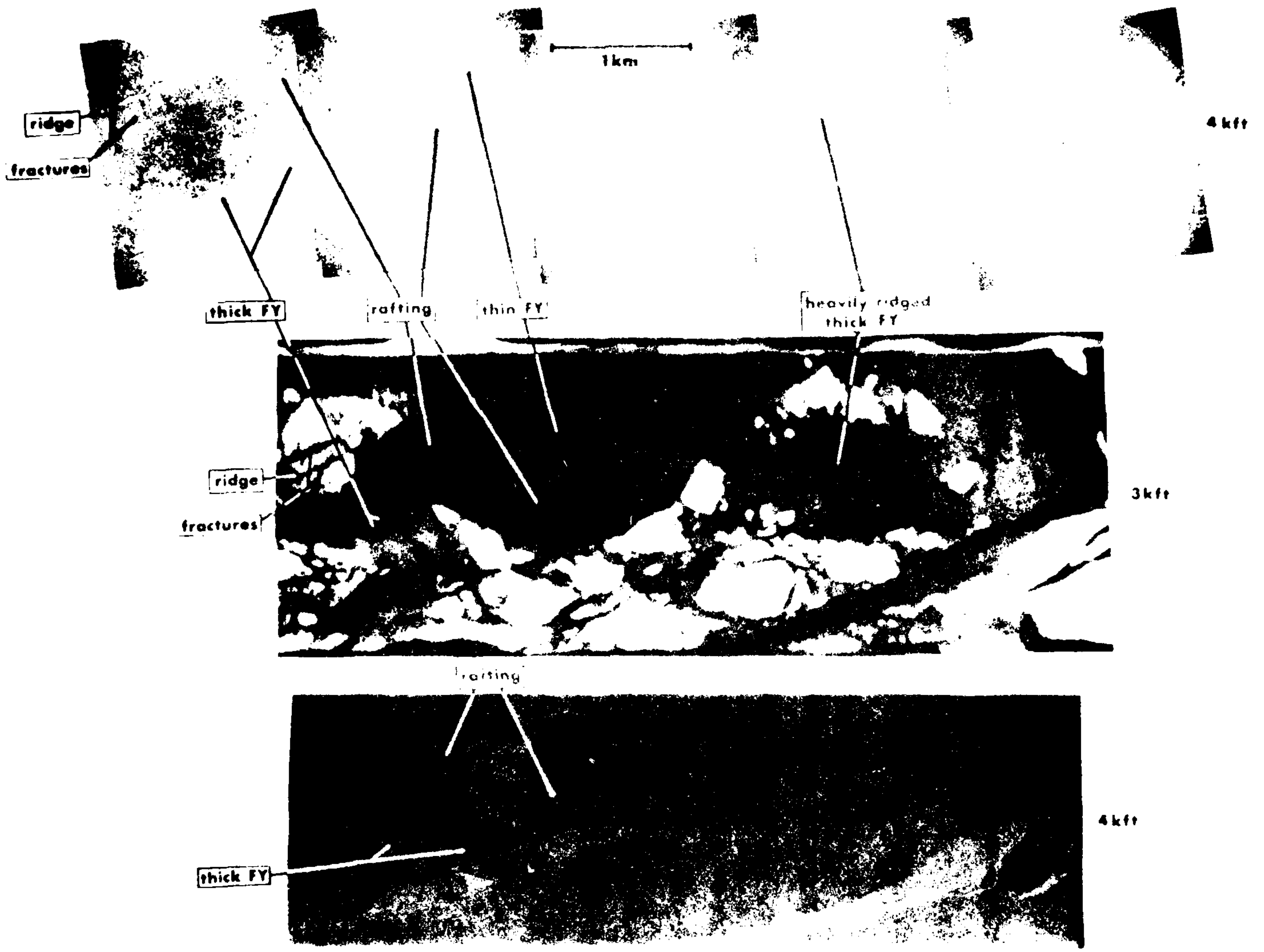

Figure 2. Photographic (top), MICRAD, and IR (bottom) Images. Radiometric Temperature Differences Between Thick First-Year Ice, Thin First-Year Ice, and Rafted Thin First-Year Ice Are Evident.

the MICRAD imagery. Confident distinction is impossible. The new ridges stand out clearly as warm radiometric lineations in the radiometrically cooler multi-year ice, but they are not similarly distinguishable against a radiometrically cool thick first-year ice background.

Ridged ice, which has been pushed into the air, should experience drastic physical property changes including brine drainage. If we assume that the physical changes which occur in these deformed features are conducive to the development of a low-loss medium, then we know that these features become somewhat transparent to radiation. Thus, highly saline recent ice formations at the sea level base of new ridges could be responsible for their relatively high radiometric temperatures. This model would also help to explain why new ice ridges are generally indistinguishable from a background of first-year ice. The radiation source layers have similar physical properties, and consequently, nearly equivalent levels of radiation.

Most of the multi-year ice floes shown in Figure 2 display abnormally low radiation temperatures. Most of these floes are relatively small as a result of prior deformational activity. The many ridges, shown by the photography, provide good evidence of the extent of the deformation which has occurred earlier.

The available data in this analysis indicate a definite relationship between ice field deformational activity and low radiometric temperatures. A good example of this relationship is shown in Figure 3. Much of this area has suffered from extremely severe deformational activity. The many new ridges and hummocks shown on the photography indicate that a great deal of floe interaction occurred during the months immediately prior to this imagery. The lowest radiators are the multi-year ice floes, mostly smaller floes, derived from larger floes during deformational activity.

Because older and thicker ice is less elastic than the more recent ice forms, old ice is more amenable to permanent crystal structure deformation. It appears that a deformed ice crystal structure and/or a change in ice porosity, due to stress, may decrease ice emissivity. The smaller multi-year ice floes are generally the ones that will display low radiometric temperatures over their entire areas. This would be expected since distribution of a high stress field throughout the cross-sectional area of a small floe is more probable than with a large floe. Often relatively small radiometrically cool areas are seen in large multi-year ice floes which otherwise produce intermediate radiometric temperatures. These low radiation areas could well represent smaller floes which experienced high stress in the past and since have combined with other ice forms in the development of a larger floe. In addition,

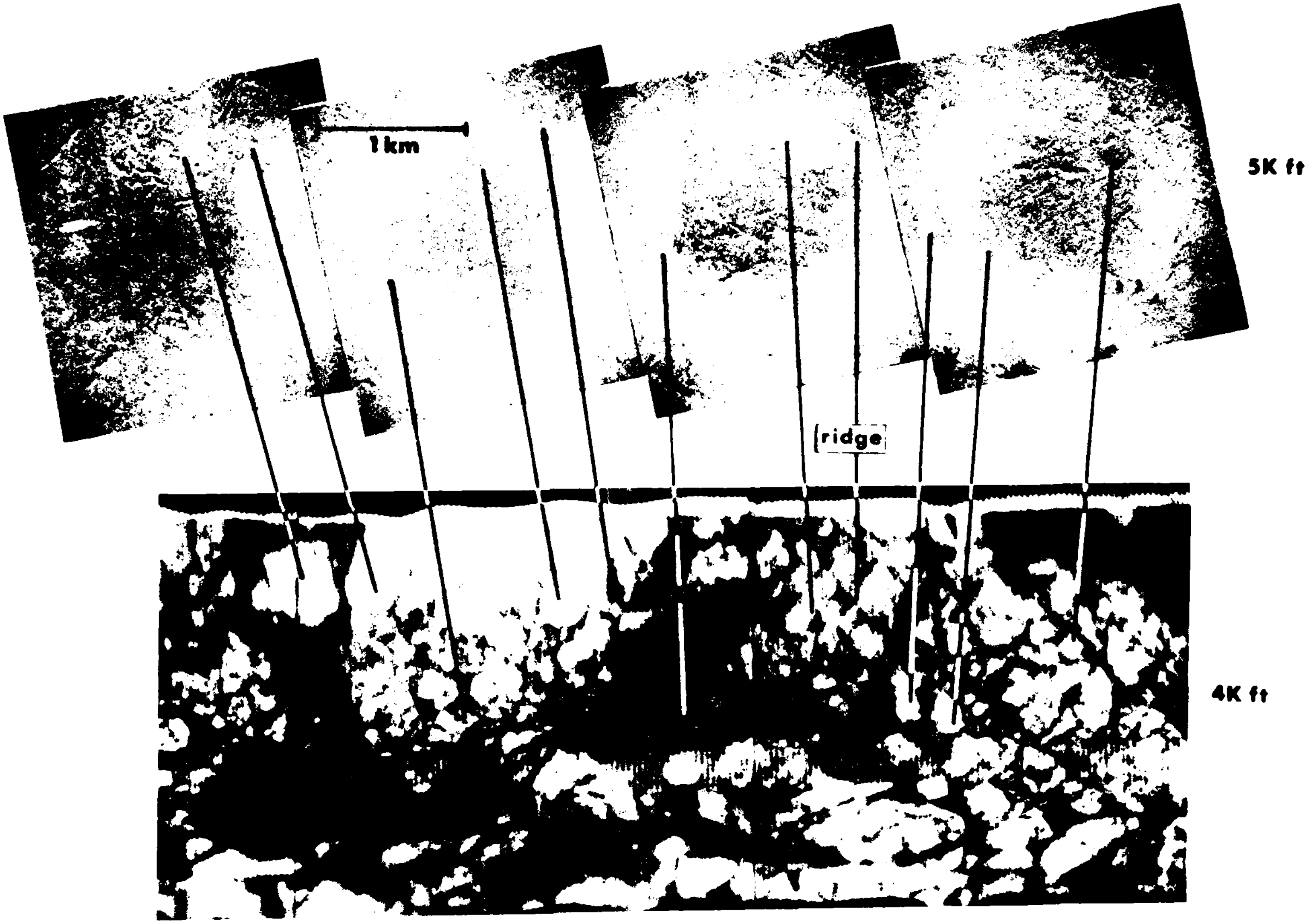

Figure 3. Photographic (top) and MICRAD Images Display an Ice Field Which Has Experienced Severe Deformational Activity.

it has not been uncommon during this analysis to find that some portions of the border areas of larger multi-year floes appear radiometrically cooler than the interior area. These low emissivity border areas may represent the extent of high stress concentration within the floes during past deformational disturbances.

The rafting in the light nilas on the left end of the strip in Figure 4 is very recent. In fact, the process may have been underway when the imagery was taken. Sea water which has been flooded onto the ice during the rafting process is evident in the photography and thermal IR imagery. There is evidence of the presence of the rafted ice on the MICRAD imagery in the form of low radiometric temperature signatures.

Two very old areas of multi-year ice appear in Figure 4, both displaying a wide range of radiometric temperatures. The high radiation areas on these floes represent frozen melt pools which are comprised essentially of fresh water ice from summer snow and ice melt. The large size and irregular pattern of the melt pools attest to the age of these two areas. On the photography much of the surface of the flat, wind swept frozen melt area is depicted as bare ice. The bare ice appears warmer on the thermal IR imagery because of absorption of solar radiation.

The earlier description of stresses producing internal crystal structure deformation which results in a reduced emissivity, means that the predominance of light-toned (low radiation) areas within the floes shown here would indicate that they have experienced considerable stress.

The other areas of multi-year ice in this scene present a much more homogeneous and characteristic appearance. The low radiation feature bisecting the multi-year ice floe in the upper center section of the imagery is believed to be a "stream bed" over which fresh water has been drained from the floe surface. The high radiometric temperature is attributed to frozen fresh water in this trough.

The area of Figure 5 is largely covered with multi-year ice which displays a relatively homogeneous radiometric temperature distribution. The long continuous new ice ridge at the left stands out sharply as a high radiation lineation against the multi-year ice background. The interesting features in this scene are the light-toned, low radiation lineations which appear in the relatively high radiation wedged shaped area which has been identified as second-year ice (SY). Some ridging and apparent, but indistinct, interfinger rafting have occurred in this same zone of thick ice, and these features are closely associated in location with the low radiation lineations seen on the MICRAD imagery. These lines may represent lines of

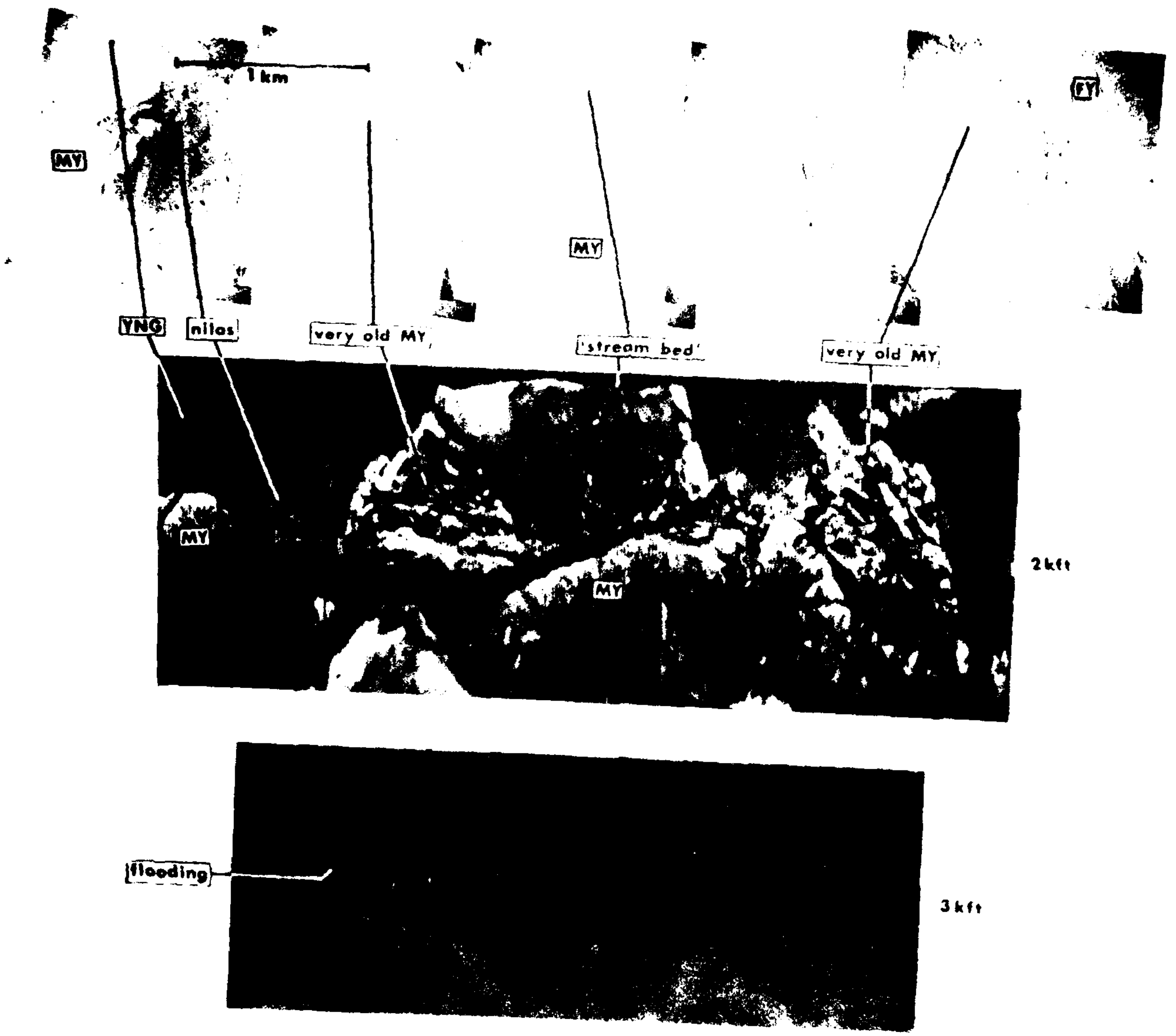

Figure 4. Photographic (top), MICRAD, and IR (bottom) Images. Two Very Old Multi-Year Ice Floes Interpreted to be Strongly Affected by Summer Melt and Ice Field Stresses Are Shown.

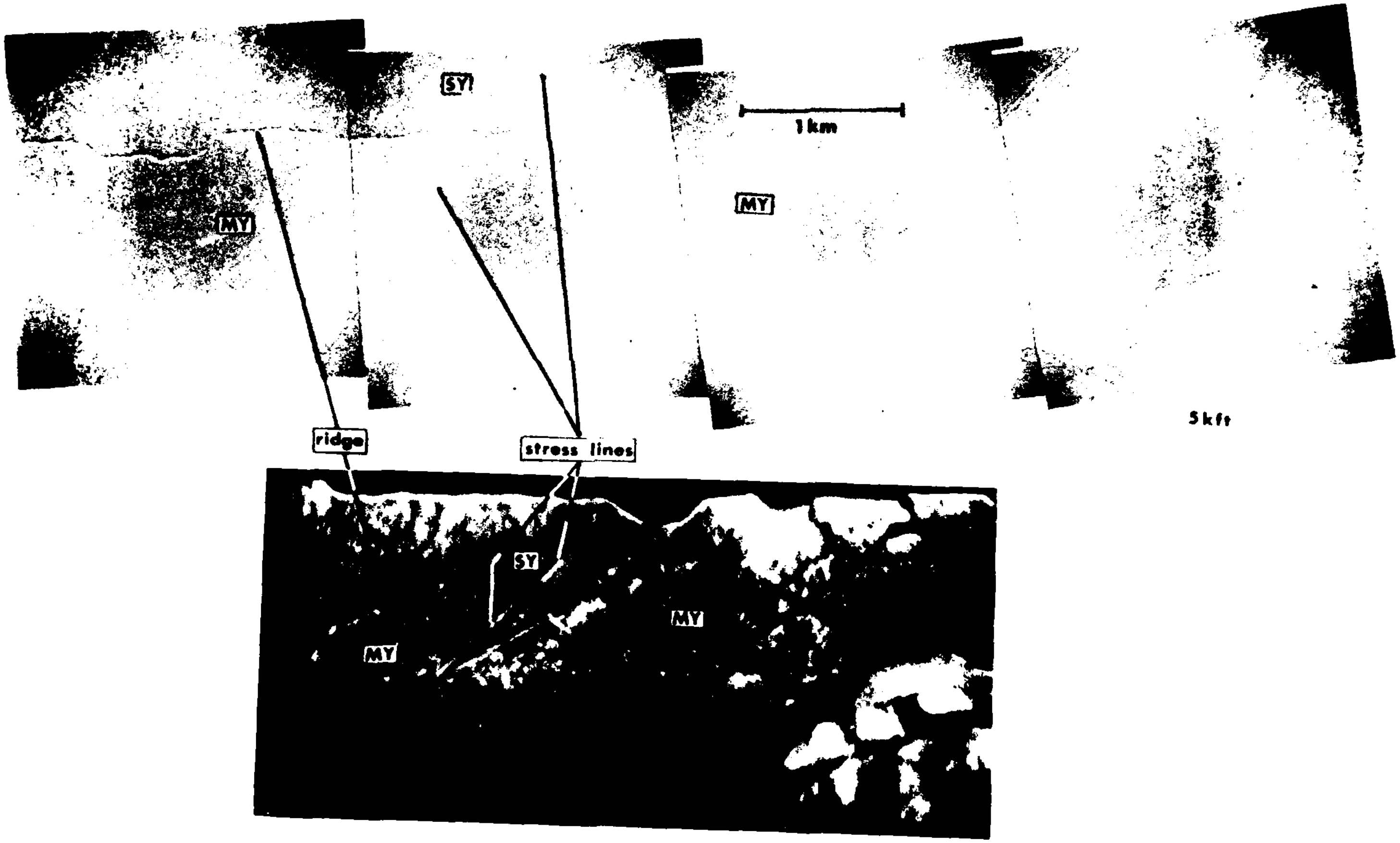

Figure 5. Photographic (top) and MICRAD Images. Low Radiation Lineations Are Interpreted as Stress Lines.

stress caused by shear or compressive forces along which ice crystal structure deformation has occurred as a result of interaction between the multi-year ice floes bordering this area. It is plausible that stress lines and zones, otherwise invisible, may be identifiable using microwave techniques.

A similar example of low radiation lineations is shown in Figure 6 in an area of thick second-year ice lying between multi-year ice floes. Although these lineations are in an area in which past rafting is evident, there is very little or no surface expression on the photography for them. The evidence shown in this analysis has strongly indicated a direct correspondence between stress in ice and low radiometric temperatures. The possibility that these low radiation lineations may represent invisible stress zones (and potential fracture zones) cannot be overlooked.

CONCLUSIONS

Because of its higher spatial resolution, the MICRAD imagery has revealed new information about sea ice radiometric temperature distribution and has raised new questions and opened new avenues for sea ice research.

The hypotheses presented here require further development through in-field observations and laboratory study.

The detection of stress fields or stress lines in the ice through the use of microwave techniques is a new concept which deserves serious consideration and attention. Future microwave observations and measurements from surface or airborne platforms should include stress, or ice crystal deformation and/or porosity, as a factor to consider when designing the field experiment. Laboratory studies could also reveal relationships between ice stress and microwave radiation.

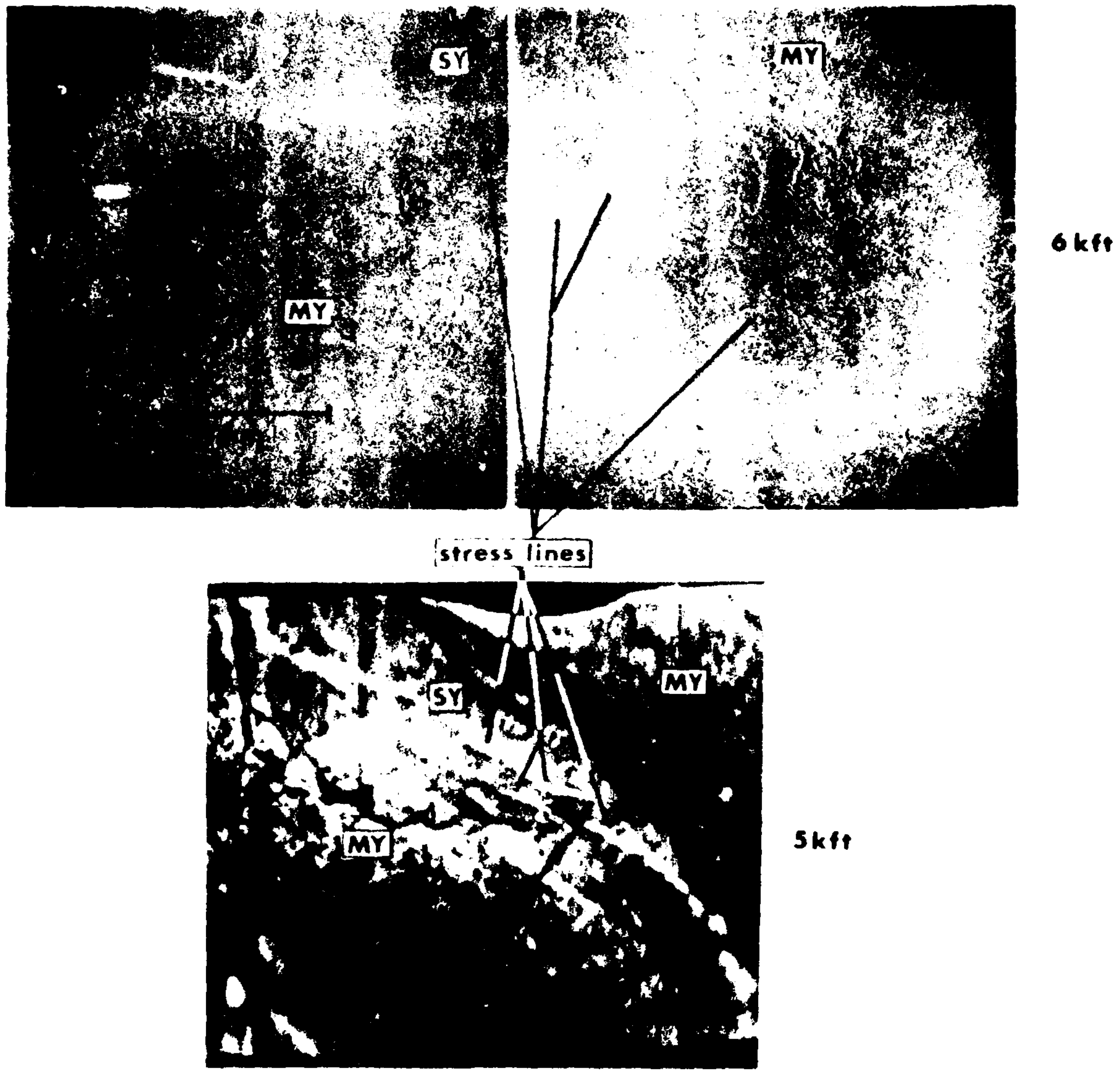

Figure 6. Photographic (top) and MICRAD Images. Low Radiation Lineations Are Interpreted as Stress Lines.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An evaluation has been conducted of passive microwave imagery which displayed many different sea ice forms and features of varying age and thickness, and in various stages of formation, deformation, and weathering. The lowest radiometric temperatures. (i.e. brightness temperatures) were displayed by open water, some areas of new ice which presumably had moist surfaces, and some multi-year ice floes and other forms which apparently had experienced considerable internal stress. It has been hypothesized

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that internal ice structure changes brought about by severe stresses result in a lowered emissivity. The highest radiometric temperatures were displayed by areas of thin ice which presumably no longer had a wet surface. new ice ridges, and frozen melt ponds. The older, thicker areas of first-year ice appeared to have lower radiometric temperatures than the thinner areas of first-year ice. Single multi-year ice floes often display a wide radiometric temperature range. This has been attributed to physical property changes which resulted from summer melting and erosional processes, and from stresses produced by the interaction of floes.

The detection of stress fields and/or stress lines through the use of microwave techniques is a new concept developed by evaluation of this data. This concept invites further investigation.