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NEWS AND NOTES

Applicability of Synthetic Aperture Radar Data for the Study of Snow Dune Complexes and Snow Sheets in Antarctica and their Bearing on Paleo-Climatic Variability

K.S. Misra[1*] and Anshuman Misra[2]
[1]Department of Petroleum Engineering and Earth Sciences, University of Petroleum and Energy Studies, Dehradun.
[2]Department of Geology, Doon University, Dehradun.
***E-mail:** *drksmisra@gmail.com*

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Synthetic Aperture Radar (SAR) data is exceptionally useful in providing nearly three-dimensional view with enhanced relief features. It has capability to measure surface roughness, thus enhances subtle relief features to present nearly three dimensional picture of the terrain. It also has fairly good capability to penetrate the snow cover and provides information about underlying solid ice. Furthermore, it measures dielectric constant which is highly sensitive to water content and thus distinctly helps to demarcate various glacio-morphic features, particularly in coastal regions of Antarctica. Compacted Snow Dunes (CSD) of Antarctica have been engaging the attention of glaciologists ever since they have been identified for the first time by Swithinbank (1988) in eastern Antarctica. He differentiated them from clouds by constant pattern in multi-date Landsat imagery and described them as mega-dunes. Fahnestock et al. (2000) described them as extremely gentle waves and stripes in snow and suggested that these features have been carved on ice sheets by relentless katabatic winds. They also estimated from the Advanced Very High Resolution Radiometer (AVHRR) images, that more than 300,000 sq. km is occupied by dune fields in eastern Antarctica. However, as studies progressed many more areas with prolific distribution of dunes are identified. Shuman et al. (2011) calculated that 900,000 sq km area is occupied by dune complexes. During our studies, we interpreted mosaic of SAR data from Canadian Radarsat as well as European Space Agency's Sentinel 1 and 2 images and located three new areas. Two are located west of Amery bay and one very close to the south pole (Fig 1). Furthermore, large peripheral areas were located around three earlier reported regions. In this way Misra et al. (2023) added more than 100,000 km area. Misra and Dobhal (2015) on the basis of their characteristic shape, size, distribution and wind direction, categorized them as 'fore-dunes'. As these fore-dunes are highly compacted, we prefer to describe them as compacted snow dunes.

Snow Dune Complexes and Snow Sheets

Snow Dune Complexes (SDC) are the most fascinating glacio-morphic features on the surface of Earth and reveal a lot about paleo-climate changes in the pristine Antarctic continent. Earlier it was believed that these complexes have formed by the katabatic wind erosion on ice sheets. Our interpretation of SAR and other optical images, suggests that the individual dunes are transverse "fore-dunes", characterized by gentle wind-ward and steeper lee-ward sides. Their deposition and compaction has taken place during very severe climatic conditions which were cyclic and correspond with the Quaternary wet interglacial and arid glacial periods. Humid periods were dominated by moisture laden wind blizzards, long duration very heavy snow fall and accumulation of exceptionally long often up to 100km linear ridges, perpendicular to the wind direction. Arid glacial periods were marked by dry winds, compaction and often with glazed lee-ward surfaces. Similarly, during following less severe glacial and inter-glacial periods, snow sheets were deposited on top of dune fields, pile ups along topographic highs and valley fills. Later compaction has stabilized these snow sheets. Furthermore, the prevailing and paleo-wind directions coincide with each other and this indicates that there has been no change during last two million years. We believe that compacted snow dunes and snow sheets can be utilized as new parameter, for fine tuning the sequence of global climatic changes.

Perhaps the best utilization of Canadian RADARSAT images has been made in the study of glacio-morphic features, particularly the snow dune complexes of Antarctica (Misra et al. 2023). Individual snow dunes are of low amplitude generally 2 to 4 m in height, very long, often extending up to 100 km. Secondly, it has emerged that they represent original snow dunes which have been subsequently compacted during intense cooling and favourable conditions. Furthermore, they have very regular shape and exactly same pattern in all the regions. Although they are remarkably linear, certain amount of sinuosity is invariably present apart from swelling and pinching along their length. Glacio-morphologically compacted dune fields predominantly occupy plateau regions around highlands generally located between 2500 to 3500 m asl and have remarkable stability. Within the fields, the distribution of dunes is controlled by the vertical tectonics. Uplifted linear blocks have well preserved dunes, while downward moved blocks have snow filled valleys. These valleys are narrow in comparison to the uplifted blocks (Fig 2).

Their long and linear shape matches with the longitudinal (sief), dunes seen in various desert regions as well as on planet Mars (Fig.3). These longitudinal dunes form along the wind direction and do not have gentle wind ward and steep lee ward sides.

SAR Images and Mapping of Snow Dunes

Synthetic Aperture Radar (SAR) data has capability to image not only during inclement weather conditions such as cloud, haze and mist cover but also during the dark winter months in Antarctica. Furthermore, satellite SAR data measures the "backscatter" or reflected energy from the top 2 to 20 meters of the snow surface, its roughness and enhances relief to provide nearly 3-dimensional picture of the terrain. RADAR tones are largely controlled by the look angle and surface roughness; rough faces scatter more energy, making it appear bright, while the smooth surfaces reflect away from the sensor making them appear dark. The dune fields therefore appear as alternating light

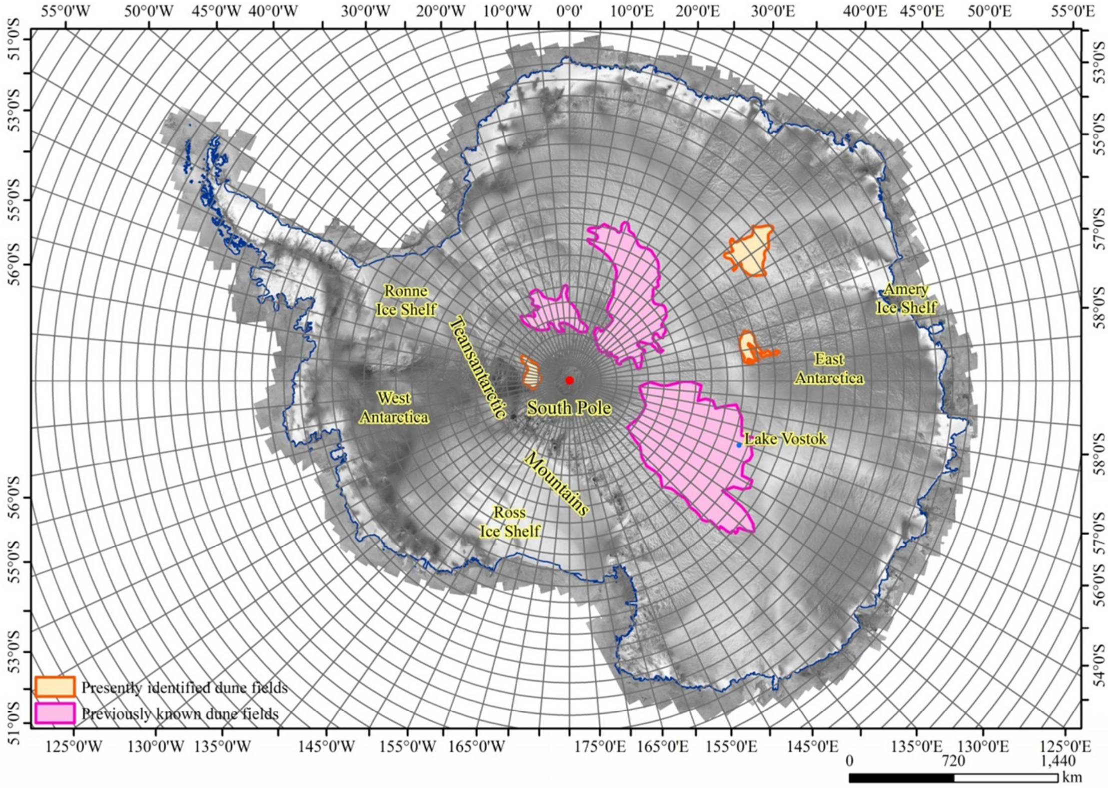

Fig. 1. Mosaic of Synthetic Aperture Radar data from Canadian Radarsat 1. It can be seen that three new areas are identified and extensions around known areas are also demarcated. (Modified after Misra et al 2023)

and dark bands. The present study utilized data from Antarctic Mapping Mission (AMM-1) and Modified Antarctic Mapping Mission (MAMM) of 1997 and 2000 respectively.

Fahnestock *et al.*, 2000 concluded that the mega dune patterns in part of the largest dune field have remained unchanged during preceding 34 years. Misra et al. (2023) used Sentinel 2 data of the 2021 (Fig. 4) and concluded that there is no change thereafter, suggesting that the dune complexes are quite stable for more than half a century old. Geomorphological evidences such as the covering of dunes by stabilized snow sheets as well as later obliteration in the glacial catchments, suggest their formation during earlier inter-glacial period.

Deposition and Compaction of Snow Dunes and Snow Sheets

Trends of the dune crests are perpendicular to the directions of katabatic winds was observed by Parish and Bromwich, (1991). Fahnestock et al., (2000) proposed that the dune formation might have started as a disruption of the wind by small hills in the ice, probably representing hills and valleys in the bedrock, hundreds of meters below the surface. However, our study of the entire eastern Antarctica has brought out very regular pattern and does not support either the idea of rippling effect or isolated hills as obstruction to deposit these dunes. Arcone and Jacobel (2009) recorded several-meter-thick co-sets with preserved bedding surfaces under the glazed lee-ward faces. Scarchilli et al., (2010) observed and measured maximum blowing snow is transported during March to August months in Antarctica. These extraordinary blowing snow transport events alternated with compaction and formation of glazed surfaces. Profiles across prograding wind-ward sides have shown more than 100 m thick layering continuing all along the length of the dunes. Shuman et al., (2011), derived elevation profiles from ICESat data and reported accretion on wind-ward sides and an intricate relationship between accumulation

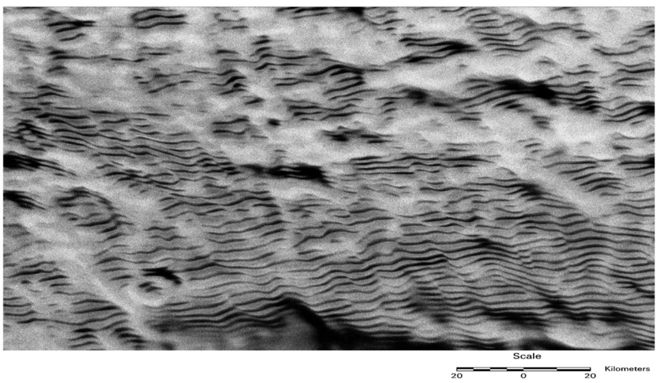

Fig. 2. Synthetic Aperture Radar image of part of eastern Antarctica, showing the compacted snow dunes. They are characterized by darker tones, linear shape and very regular pattern. Light tone areas are covered by consolidated snow sheets.

Fig. 3. Longitudinal dunes on the surface of Mars. Very strong arid winds have aligned even the big boulders along the dune axis.

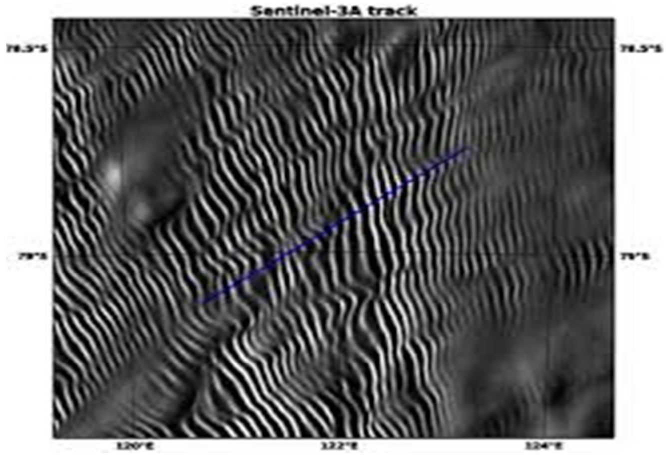

Fig. 4: Sentinal 1 SAR imagery showing compacted snow dunes. Snow sheets covering the dunes can also be seen.

rate and surface profiles. Dadic et al. (2013) reported that the prevailing katabatic winds are perpendicular to the longer axes of snow dunes. Misra and Dobhal (2015) observed that accumulated snow ridges represent original snow dunes, compacted subsequently during intense cooling in favourable conditions. Meteorological data from the interior of the eastern Antarctica, indicates that the dune areas are characterized by katabatic wind flow having constant speed and uniform direction. During the present study, most important support for the formation of compacted dune complexes has come from the geomorphic principles. It has been observed globally that depositional landforms have regular patterns while the erosional ones are highly irregular and erratic. Geomorphic and glaciological evidences gathered during the present study, suggest that dune complex have formed following two stages. In first stage, the falling snow crystals are piled up by moisture laden winds, during wet inter glacial periods. Later in second stage, consolidation and compaction has taken place due to intense cooling in intervening glacial periods. Metamorphism and growth of crystals continued during compaction. Radar and satellite images show feature of compacted dunes that suggest alternating fine and coarse grains, alternating with rough and smooth surfaces. These surfaces are indiscriminately covered by overburden of consolidated snow sheets. Wherever, the thickness is less, clusters of snow dunes can be seen through them. Furthermore, these sheets cover well-formed dunes, it is visualized that they have accumulated under slightly different climatic conditions, separating them from dune fields due to lack of moisture and low wavelength. Similarly compacted and lithified Quaternary calcareous parabolic dunes are mapped in coastal Saurashtra. Dune complexes of several generations are recognized, which seem to be related to alternating glacial and inter glacial cycles.

Dune Complexes and Climate Change Parameter

Presently, the Antarctic continent experiences dry and cold climatic conditions making it as largest cold desert. There is no precipitation either as rains or snow. However, in recent years, possibly under the effects of global climatic changes, a little precipitation has been recorded in peripheral coastal regions. Misra and Dobhal (2015) and Misra et al. (2023) emphasized that the study of compacted dunes can help in understanding the effects of alternating glacial and interglacial periods. These effects have been studied and documented in different parts particularly Europe and North America. Four major and more than hundred minor ice ages have been identified. Severity of unusual blizzards lasting for several months and dumping huge amount of snow are reported from North America in historical times. It can be visualized that these effects must have been more severe in icy Antarctic continent. In large areas the dune fields are covered by snow sheets. These sheets seem to have also followed two stages, corresponding with the dune formation however, certain variations such as moisture content, amplitude and wavelength of corresponding winds. Glacial and inter glacial periods, however, continued after the formation of dune complexes and snow sheets. This is evident by the development of enormous glacier catchments, where dune fields are later obliterated, suggesting that this event postdates dune formation.

These enormous climatic variations of continental proportions are mapped and seem to correspond with glacial and interglacial periods throughout the geological history of the Earth. Evidences of first major well recorded glaciation came from the Proterozoic Era. During Permo-Carboniferous period, the inter-glaciation provided hot humid climate for the luxuriant growth of forests, less carbon dioxide and lot of food to support diverse fauna and beginning of giant reptiles. Intense glaciation destroyed the forests and the logs got deposited in rifted river valleys to form coal seams. The latest glaciation and inter-glaciation has taken place during the Quaternary Era. Giant woolly mammoths evolved during the inter-glaciation and became extinct due to loss of vegetation following intense cold glacial period.

The exact nature of the compacted snow dunes in totality has emerged during the study. As stated earlier. the dunes have gentle windward and steeper leeward sides and have formed perpendicular to the wind direction. Prevailing as well as paleo-wind directions which have formed these dunes match together. This suggests that the wind directions have not changed ever since their formation. They are the product of accumulation of snow and have not been carved on ice sheets as believed earlier by some scientists. Glazed surfaces, however, developed by wind polishing are present only on the lee ward sides. Further our study suggests that the dune complexes covered almost entire eastern part of the Antarctica, indicating that climatic conditions were of continental nature and were not confined locally. The dune complexes largely occupy elevated regions. The prevailing climatic conditions during summer and winter months were similar to those, existing in the past, however, they were very severe and long corresponding with glacial and inter-glacial periods during Quaternary era. The relentless winds were also severe when they formed the compacted snow dunes by moisture laden blizzard winds. The intense blizzard conditions with enormous snowing and accumulation prevailed in almost entire eastern Antarctica. Stabilized snow sheets overlie the dune regions like an overburden. Many a time dunes as well as dune like patterns can be recognized wherever burden is thin. Weather conditions were similar to those prevailing presently, however, the magnitude was very high and also continued for a much longer time. Similarly, consolidated snow sheets have formed under slightly different weather conditions. Other intriguing features associated with the compacted snow dunes are their low height and fairly wide lateral separation. This could be because of amplitude and wavelength of winds prevailed during their formation.

Snow dunes as well as snow sheets are the product of aeolian (wind) action. The desert winds are dry and change direction with season as well as between day and night. Polar winds prevailing over Antarctica are not affected by these factors and have uniform directional (katabatic) flow. However, during seasons and climatic conditions their moisture content has varied. Severe snowing with moisture laden winds (blizzards) were ideal for accumulation and much cooler glacial (ice age) conditions favoured compaction and metamorphism. Furthermore, their distribution suggests that they covered almost entire eastern Antarctica. Their separation is found to be dependent on three factors, such as preferential preservation on highlands, later indiscriminate covering by snow sheets and selective destruction by ice sheets as well as glaciers. Extensive distribution and similarities have led us to believe that the event responsible for their formation was of continental extent. During the formation of desert dunes and sand sheets, particles of different sizes move by rolling and jumping (saltation) along the wind direction. In case of snow dunes, the falling crystals being lighter glided to long distances. It appears that this is mostly responsible for large separation between the dunes. Furthermore, the amplitude and wavelength of flowing wind could have played vital role in geometric similarity and vast extent.

Compacted snow dune complexes have formed following mainly two stages, during first stage enormous snow fall accompanied with high moisture content severe winds accumulated in the form of fore-dunes. This coincided with the wet inter-glacial period. Later during glacial cycle compaction and metamorphism of accumulated snow and development of glazed surfaces by wind polishing. The disposition of snow dunes is having a very high degree of uniformity and regularity. Depositional landforms have uniformity and regular pattern whereas erosional landform is irregular, erratic and random. The Earth has experienced glacial and inter-glacial periods throughout the geological history and they were most intense in Antarctic continent. The paleo-wind directions deduced from the study of compacted snow dunes and snow fields correspond with the prevailing wind direction.

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