SNOW MICRO PENETROMETER AND NEAR INFRARED PHOTOGRAPHY FOR GRAIN TYPE CLASSIFICATION.

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ABSTRACT: Avalanche formation and remote sensing of snow water equivalent are dependent on snow stratigraphy and grain type. Time-intensive manual snow pit profiles are currently used to determine snow pack properties, which are highly dependent on observer skill and experience, and are inherently subjective. The Snow Micro Penetrometer (SMP) and Near InfraRed (NIR) photography are two tools that are sensitive to snow microstructure and can be used to classify the snow grains into three main types: new snow, rounds, and facets. SMP and NIR measurements were taken side-by-side at 8 manual snow pits located on Grand Mesa in Colorado during the 3rd NASA Cold Lands Processes Experiment (CLPX-III). A classification tree using SMP force and micro-structural properties, and NIR reflectance, is able to determine the three grain types with 92 to 95% correct classification accuracy. Though more data is needed to perform a robust analysis and the results here are reported as preliminary, the combination of NIR and SMP tools appears to be promising for snow grain classification.

KEYWORDS: Snow Micro Penetrometer, Near InfraRed photography, grain classification

1. INTRODUCTION

Knowledge of snow type and stratigraphy is the basis for many snow related problems. Being able to quickly and accurately quantify grain type as well as stratigraphy can help improve our understanding of avalanche formation and release, improve retrieval algorithms for remote sensing of snow water equivalent (SWE), and improve our understanding of horizontal and lateral water flow within the snowpack. Manual snow pit profiles are currently the standard for measuring snow stratigraphy, grain type, and hardness. However, this method is highly subjective, time-intensive, and dependent on the observer's skill as small layer boundaries and hardness transitions can be overlooked (Pielmeier et al, 2003). Therefore, objective, accurate, and time efficient instruments need to be used to determine layering, grain type, and hardness with high resolution. This study reports results regarding attempts to classify grain type using the Snow Micro Penetrometer and Near InfraRed photography from a continental snowpack.

Snow hardness and stratigraphy can be measured with the high resolution Snow Micro Penetrometer (Johnson and Schneebeli, 1999). The Snow Micro Penetrometer (SMP) is a constant velocity penetrometer that measures the penetration resistance with a force resolution of 0.001 N and a vertical resolution of 0.004-mm. Micro-structural and micro-mechanical properties such-as strength, modulus of elasticity, and structural element length can be determined from the signal's geometry, and are calculated using the improved analysis procedure described by Marshall and Johnson (2009).

Near InfraRed (NIR) photography measures the reflectance of the snow pit wall. Using calibration targets of known reflectance and a reference board for normalization of the digital image, the snow reflectance can be retrieved accurately and quickly, usually in less than 10 minutes. The reflectance is mainly a function of the specific surface area (Matzl and Schneebeli, 2006), the optical grain diameter, and relative grain shape (Langlois et al., 2010). Higher reflectance is typical of smaller, spherical grains that have large specific surface area, with decreasing reflectance as the grains become larger, and less spherical.

2. METHODS

Measurements were taken during the 3rd NASA Cold Land Processes Experiment (CLPX-III) on Grand Mesa, Colorado in February 2010. Manual pit observations were performed, classifying the stratigraphy, density, temperature, and four main grain types: new snow, rounds, facets, and mixed (mixture of rounds and facets). Simple grain types are used to save time in the

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pits and for remote sensing retrieval algorithms. Four SMP measurements were taken behind the pit face at 20 pit locations. NIR photographs were taken at 8 of these pits.

2.1 SMP Analysis

A database of SMP signals was created for each grain type by manually picking the layers from each profile to remove layer transitions. For each layer sample, the force statistics, mean (MF), standard deviation (SD), and coefficient of variation (CV), were calculated for a 10 mm moving window with a 1 mm step size. The MF, SD, and CV were averaged over the layer thickness to produce the mean layer statistic. The average layer micro-mechanical and micro-structural properties were determined using the same method. Two different classification trees were grown, one that included force statistics and the other included force statistics and micro-structural properties. Table 1 shows the number of SMP samples for all 19 pits, 4 pits had 3 profiles and rest had 4 profiles.

The best predictor variables were chosen using Cross-Validation and Monte Carlo simulations over all 19 pits. 1000 trees were grown and the most frequent predictor variable at each node was used to create the final trees. The optimal split values were determined by minimizing an error function based on the average misclassification rate for all grain types. The error function uses an estimate for the node values to classify each SMP profile individually, determining the most frequent grain type in all the profiles for each millimeter. The classification was filtered to assure that new snow was not under rounds or facets and layers less than 10mm were set to the surrounding grain type. The misclassification rate for each grain type was calculated:

$$MC = 1 - \frac{\text{true positive} + \text{true negative}}{\text{number of points}} \qquad (1)$$

where true positive is a correctly classified point and true negative is when the grain type is correctly not predicted. The misclassification rate was calculated for each grain type and then averaged for the overall pit accuracy. The results were the best split parameters that minimized the overall misclassification rate.

2.2 NIR Analysis

A database of NIR reflectance was created for each grain type by using the manually picked layers from the SMP analysis. For each layer sample, the force statistics, mean (MF), standard deviation (SD), and coefficient of variation (CV), were calculated for a 10 mm moving window with a 1 mm step size for the entire image. The MF, SD, and CV were averaged to produce the mean layer statistic.

The best predictor variables were chosen using a random and equal sample size (4 samples) from each grain type, which removes bias that may occur from using the entire data set. This process was repeated 10^3 times and only large enough trees (7 nodes) were used to determine the split variables. The image was classified vertically, obtaining a grain type profile for each pixel over the width of the image. The most frequent grain type was used to determine the overall pit classification and compared to the manual pit observations. The split values were determined by minimizing the error function (Eq. 1) for the entire dataset.

	Number of Pits	New Snow	Rounds	Mixed	Facets
SMP	19	55	159	51	63
NIR	8	5	22	5	9

Table 1. Total number of layers in database for use in SMP and NIR classification.

2.3 SMP and NIR comparison

The best predictor variables from the SMP analysis of all 19 pits were used in the comparison. Split values for both SMP and NIR classification tree were found by minimizing the error function (Eq. 1) for the 8 pits where SMP and NIR measurements were taken. The comparison quantifies how well the SMP and NIR classify the 8 pits and not future measurements.

2.4 Mixed grain type

Pit observations were classified into four general grain types: new snow, rounds, facets, and mixed. Mixed is a grain that is somewhere between a round and a facet, due to a change in temperature gradient. This grain type is hard to quantify during the classification analysis since it can include both rounded and faceted components. For the rest of the analysis, the mixed grain type is set to rounds as it minimizes the error function. This decision is also based on

	Force		Micro-Structural		NIR	
Variables	SD [N]	CV	Strength [N/mm^2]	CV	Mean Reflectance	Mean Reflectance
New Snow	< 0.0062	--	< 0.0187	--	≥ 0.9936	--
Rounds	≥ 0.0062	< 0.5386	≥ 0.0187	< 0.5386	< 0.9936	≥ 0.6014
Facets	≥ 0.0062	≥ 0.5386	≥ 0.0187	≥ 0.5386	--	< 0.6014

Table 2. Best split variables and split values for the SMP Force and Micro-Structural and the NIR classification trees.

the temperature profiles. Within each mixed layer, the temperature gradient was less than 1° Celsius per 10 cm, which indicated the mixed layers are in general undergoing equitemperature metamorphism.

3. RESULTS

3.1 SMP Classification

The SMP split variable results from the Monte Carlo and Cross-Validation simulations for the two classification trees are shown in Table 2, as well as the best split values determined from minimizing the error function for the 8 pits.

These results are only for the classification trees that set mixed grains to rounds. Both the classification trees, using force statistics or micro-structural properties, indicate that the best split parameter between rounds and facets is the coefficient of variation. Examples of the SMP signal for rounds and facets can be seen in Figure 1. The rounds produce a signal with fairly uniform amplitude whereas the facets produce a signal with intermittent large peaks that drop close to zero in the troughs.

The difference between the SMP force and micro-structural classification trees are the first split to determine new snow, where the standard deviation is replaced with micro-strength. This slightly decreases the misclassification rate for the new snow (Figure 2). The overall correct classifications for the force and micro-structural classification trees are 0.955 and 0.952 respectively.

3.2 NIR Classification

The optimal NIR split variables were determined to be the mean reflectance with split values shown in Table 2. Compared to the SMP, the NIR has a larger range of correct classification for all grain types. The overall correct classification is 0.924.

4. DISCUSSION AND CONCLUSION

The SMP can accurately classify a snow pit into three basic grain types (new snow, rounds, and facets). 95% overall correct classification rates can be obtained using three or more SMP profiles to determine the most probable grain type. Multiple profiles lessen the affect of misclassified points by averaging the grain types over a larger

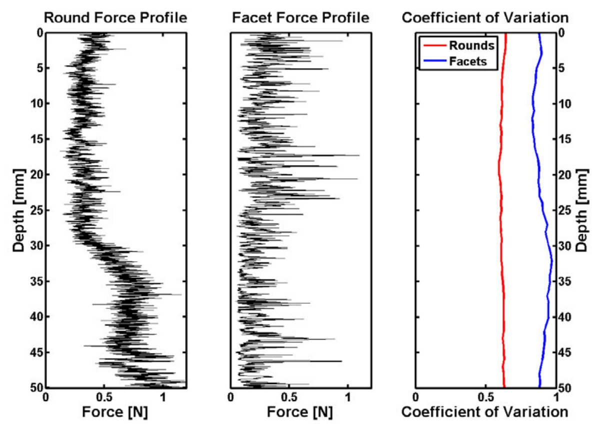

Figure 1. SMP force signals for rounded and faceted grains. The coefficient of variation values is shown for each example.

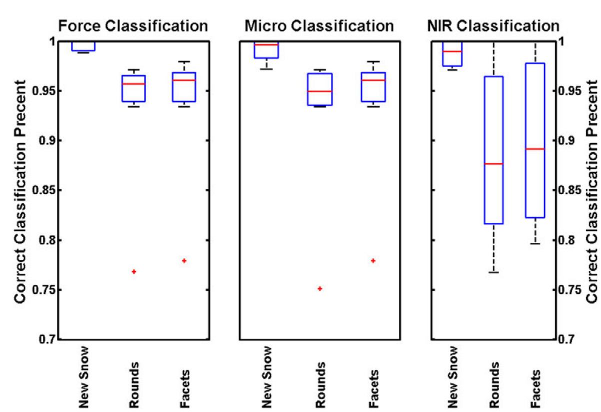

Figure 2. Correct classification percent between the SMP force, SMP micro, and NIR reflectance tree for three grain types.

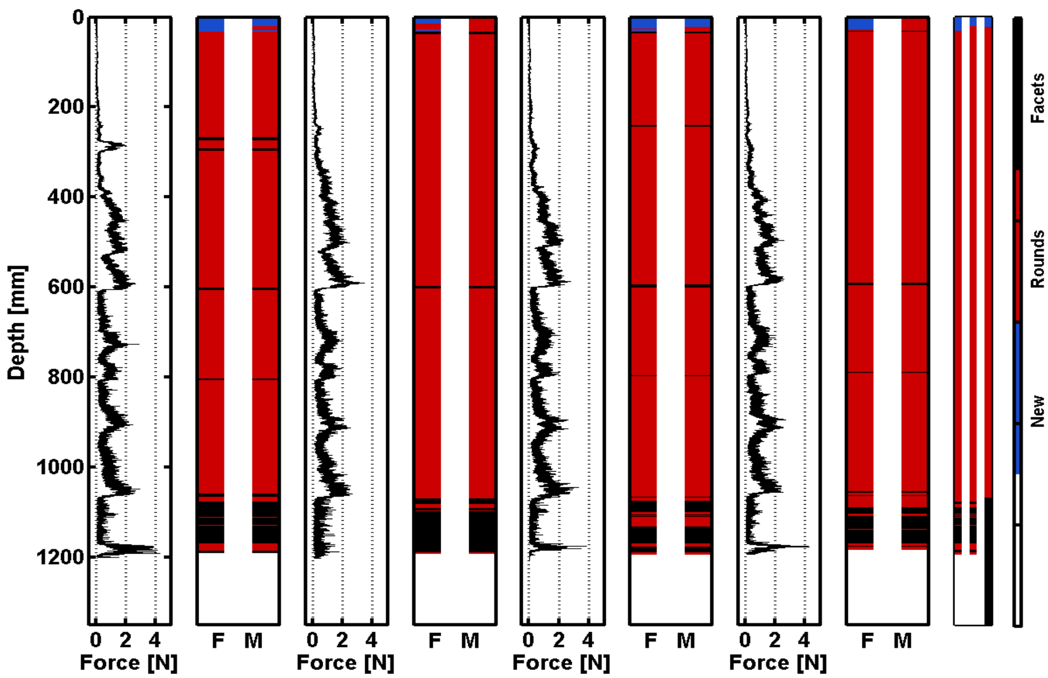

Figure 3. Four SMP profiles from one pit. The plot shows the SMP penetration force along with the classification using the force (F) and micro-structural (M) classifications. The right most panel shows the most frequent grain type for the force (left) and micro-structural (middle) classifications as compared to the pit observations (right).

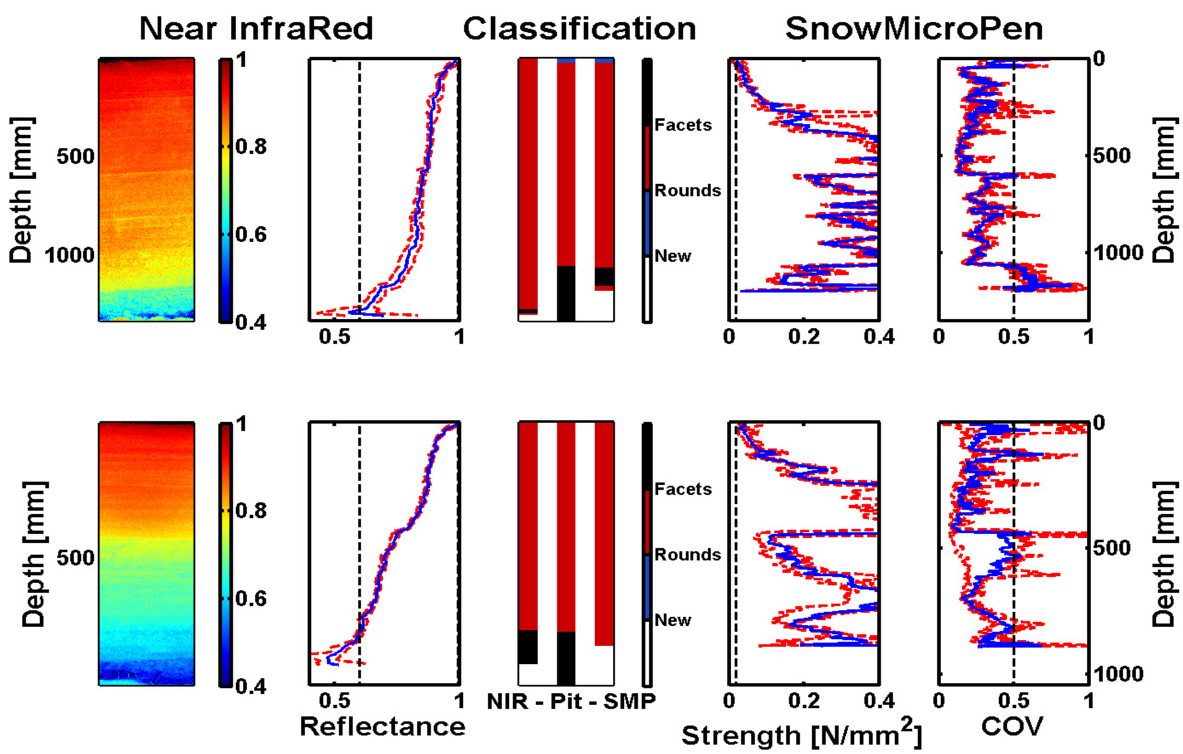

Figure 4. Comparing NIR (left two panels) and SMP (right two panels) predictor variables used in the classification trees at two separate pits. Vertical dashed lines are the split values for each variable.

support area. Full profile snow pits encompass a large support area (>1 meter across) and layer information can be averaged over the entire pit face. One SMP measurement is a point sample that may or may not obtain a representative sample of the snow. Using more than three profiles will increase the support area of the SMP measurements, which can then be compared to manual pit measurements. This can be seen in Figure 3 where the new snow is classified differently in each profile. When all four classified profiles are used to determine the most frequent grain type, the correct classification rate increases from 92% to 94% before applying the profile filter. In contrast, Satyawali et al. (2009) created a classification scheme to characterize 5 grain types, resulting in a probability of snow characterization of approximately 80% for three individual SMP profiles.

The present SMP analysis using 8 pits to determine classification tree split values shows that the benefit of using micro-structural information for classification is insignificant. The small amount of samples for each layer prevents robust classification tree analysis. Using all 19 pits for growing and testing the classification trees is beyond the scope of this paper.

The NIR has difficulty automatically picking grain type and layer boundaries from the reflectance as seen in Figure 4. This is due to the large range of reflectance values observed for each grain type. Splits between the three grain types are not definitive or consistent for all the pits. New snow is typically the top five to ten centimeters where light transmission from the surface can affect the reflectance values, making classification difficult. Reflectance is primarily a function of grain size and grain shape, which can differ greatly for a single grain type. The SMP signal is only a function of the penetration resistance where each grain type has a different signal geometry that can be easily recognized by a simple classification tree.

In conclusion, the SMP is fast (~3 min per profile) tool that can be utilized to objectively classify the snow pack with a high degree of accuracy without the need to dig a pit. In contrast, NIR photography is more time consuming and will require more investigation to determine a pertinent method for grain classification.

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