

TEMPORAL AND SPATIAL CHANGES OF A SEASONAL SNOWPACK WITHIN A SMALL SHELTERED SLOPE

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ABSTRACT: We studied the seasonal evolution of a natural snowpack and changes thereof within a small sheltered slope, utilizing non-destructive monitoring systems continuously over more than three months. During the winter season 2012, a permanent installation of a 800 MHz upward-looking ground-penetrating radar (upGPR) provided sub-daily to hourly data about variations in total snow depth, liquid-water content and major stratigraphy at a point in the center of the slope. In addition, to observe the spatial representativeness of these point measurements, we performed radar observations along a 22m aerial tramway once a week using a 1GHz GPR system. The transect crossed the upGPR location and thereby allowed us to put the point measurement in the context of the entire slope. Furthermore, conventional snow pits including densities, liquid-water content measurements and depth probings were recorded next to the tramway right before or after the above-snow measurements. An automated weather station, which was located on a ridge line right above the study slope, provided standard meteorological and snow observations. Utilizing upGPR data together with the tramway measurements, we can determine and time strain rates, new-snow amounts and percolation of liquid water in relation to the prevailing weather conditions and observe both spatial and temporal variability in these properties. The scope of this paper is to demonstrate the potential of non-destructive observations in seasonal snowpacks, to provide further information of the formation of changes in stratigraphy and the variability thereof across a slope.

KEYWORDS: upGPR, tramway GPR, temporal/ spatial variability

1. INTRODUCTION

The layering of the mountain snowpack is one of the key parameters for assessing snow stability (e.g. Schweizer et al., 2003). Monitoring changes in stratigraphy in addition to snow depth and liquid water infiltration is only possible utilizing non-destructive observation methods. Methods not affecting the recorded snowpack are either based on optical sensors (laser scan, time-lapse photography) or on electromagnetic sensors transmitting in the microwave frequency range.

Radar systems, in contrast to optical methods, enable monitoring of internal changes of snowpack properties in addition to the total snow depth (e.g. Marshall and Koh, 2008). So far two different radar applications have been utilized in snow science: (i) from above the snow surface (e.g. Vickers and Rose 1973) and (ii) from underneath the snowpack with sensors buried in the ground (e.g. Gubler and Hiller, 1984). If buried in the ground, radar systems are able to provide continuous data on temporal

snowpack evolution (Heilig et al., 2010) at a point, while surface radars can provide detailed information about spatial variations.

In this study, we combined above-surface measurements utilizing a tramway system with continuous point observations utilizing upward-looking radar. Both measurements, from above and beneath the snowpack, were conducted with commercially available impulse radar systems (GPR).

During the winter season 2012 (January-April), we continuously observed temporal snowpack-alternations at a point measurement and compared gathered signal responses on a weekly basis with signals recorded along a 22m transect. Here, we present changes in the total snow depth along the radar transect with respect to point measurements during accumulation and melt conditions. Furthermore, we follow a distinct surface signal after burial for 3 weeks and calculated strains every 0.1m along the transect.

2. METHODS

2.1 Field data

In fall 2011, we buried an upward-looking GPR (upGPR) system level to the ground at the newly developed snow-study site near the Bogus ridge

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line (2100 m a.s.l.) above Boise, Idaho. The test site (Figure 1) is within a small tree-sheltered SE-facing slope (30m x 30m upslope/ cross slope direction). Slope angle varies from about 20 degrees along the upper parts close to the ridge to almost 30 degrees at the lower part of the study site. An automated weather station was located approximately 50m from the slope at the ridge crest. The upGPR is located in the center of the slope. Tramway measurements cross the upGPR location between 15-16m of each transect. We used a RAMAC system (MALA Geoscience, Sweden) with shielded 800 MHz antennas for the upGPR. The antennas were mounted on a linear actuator to move them vertically during each radar recording.

A solar array of 180W with six 30Ah lead batteries provided power to the instrumentation. Utilizing time switches together with a field laptop, we were able to run the whole system autonomously.

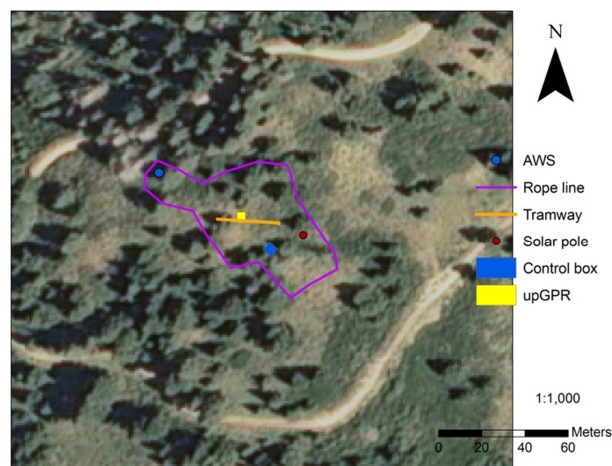


Figure 1: Test site Bogus Basin, Boise, Idaho. The slope is surrounded by trees and centered between two roads, the upper one (upper part of the figure) marks the ridge above the slope. Within the roped area (purple line) installations are displayed in the corresponding colors.

UpGPR measurements were conducted hourly from 9:00h-18:00h and 3 times during the night starting mid-February. From January 1st till then

data were only recorded every 3h during daytime due to technical problems. Tramway transects were performed almost every week coincident with conventional snow pits (Fierz et al., 2010) including density and liquid-water-content measurements utilizing a capacitance plate (Denoth et al., 1984). For GPR trace-location, we set a marker on the recorded radargram every 2m and interpolated along these markers. A maximum resolution along the transect of 0.02m distance per trace is possible, but in terms of uncertainties in the interpolation, a smoothing was applied, which reduced the resolution to 0.1m.

2.2 Data processing

Gathered radar data was processed similar as described by Heilig et al. (2010) and Mitterer et al. (2011). We applied dewow and band pass filters to reduce clutter and noise and linear gain increasing with travel time to compensate for divergence losses of the radar signal. As described above, the antenna was lifted and lowered twice during each measurement. The resulting data consists of two kinds of signals, (i) with a respective structure corresponding to the vertical movement and (ii) without any vertical oscillations in the signal. Those constant signals in (ii) are caused by system noise (e.g. multiples of the direct wave or antenna ringing) and mask snowpack-related reflections. Applying filter algorithms and lifting corrections enable elimination of these constant signals. All signals originating from within the snowpack show a distinctive movement pattern. After static correction, the resulting radar traces were stacked and the average trace for each radar observation was merged into one radargram (Figure 2). To filter reflections originating from the cover box or surrounding rocks, we applied a moving window filter with a width of 4 weeks. If a sample value of a trace (total 770 samples per trace) remained constant over a time period of 2 weeks in advance and to weeks after a specific measurement, it was considered unrelated to snow and thereby removed.

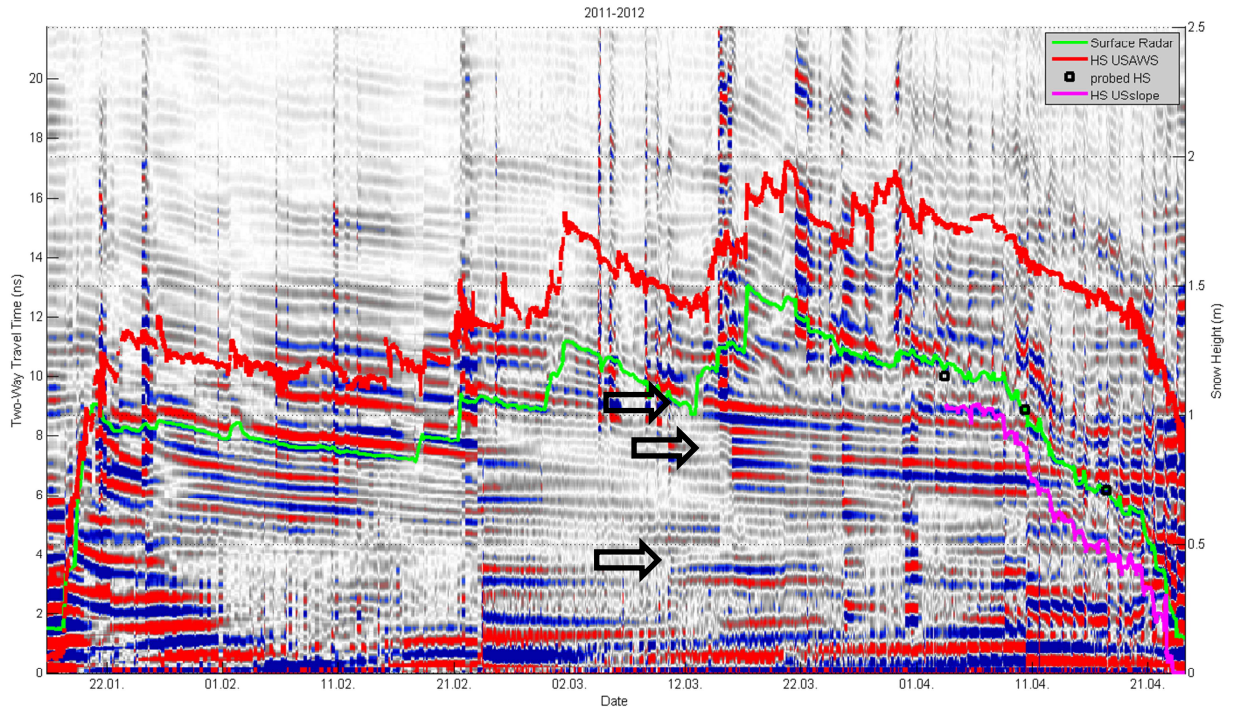


Figure 2: Plot of the entire season of upGPR measurements. Time scale ranges from January 16 until April 27 2012. The radargram is visualized such that positive amplitude values are plotted in red and negative amplitudes in blue, while color saturation corresponds to amplitude intensity. The green line represents the picked snow surface of the upGPR, red line is snow depth measured at the AWS at the ridge, purple line shows an ultrasonic snow-depth sensor installed during the season slightly above the upGPR and black squares indicate probed snow depths right above the upGPR. Black arrows indicate referred signal reflections.

3. RESULTS AND DISCUSSION

In the following, we present results of the upGPR-point measurements and relate some events spatially along the tramway transect. The total snow depth and changes thereof in relation to the upGPR point data are analyzed. Furthermore, we relate snow-depth patterns to precipitation and melt events and determine strains for 1 specific snow layer over 3 weeks.

3.1 *Temporal snowpack evolution at upGPR location*

Winter 2012 in Idaho was characterized by a dry period in early winter. Initial snowfall in late November was succeeded by a dry interval persisting through mid January, interrupted by 3 days of precipitation at the end of December. As a result an inhomogeneous 0-0.3m thick layer of old snow covered the test site when the first big snowfall event hit the slope starting Jan. 18. Within 3 days

more than 1m of new snow covered the test site. After January, only 3 more major snowfall events occurred until late April. The seasonal snowpack at the test site consisted of those 4 major accumulations interrupted by several rain-on-snow and severe melt events. The upGPR plot in Figure 2 represents these circumstances. When precipitation is predominant during upGPR measurements, multiple reflection above the surface in air are evident in the radargram as signal reflection is caused from above the surface as well. Rain can be distinguished from snow by percolating liquid water, which affects deeper layers in the snowpack and thereby results in reflection alternations within the snowpack. Snow fall, however, just has an effect on the surface reflection. Melt events cause similar effects like rain events. The surface-near layers get percolated with liquid water, which increases the permittivity there and generates strong permittivity gradients with the layer beneath, resulting in distinct reflection horizons. These reflections continue as multiples in air. Distinct rain events can be observed in the upGPR plot at the following dates:

Jan. 18, Jan. 25, Feb. 22, Mar 15.

Multiples in air, which are present at other dates not mentioned here, can be related to severe melt events. The first event which caused the stable wetting-front to percolate all the way through the snowpack happened Mar. 6. The following 6 days were characterized by warm temperatures and successive melt events. On Mar. 10 stratigraphy changed at about 0.8m above ground (Fig 2, middle arrow) and at 0.3m (Fig 2, lower arrow). On Mar. 15, a strong rain-on-snow event accumulated liquid water above those layers. The lower layer at 0.3m disappeared with the next melt intrusion to the ground, which happened Mar 25-26. However, the layer at 0.8m and the former surface at ~1.0m, which got buried by new snow starting Mar 13 (Fig 2, upper arrow), remained detectable in the upGPR radargram until those layers melted in late April.

Mitterer et al. (2011) calculated the stored volumetric liquid water content (LWC) utilizing an externally determined snow depth above/close by the upGPR location. This work was performed on a flat site with a slope close to 0 degrees. However, they observed a distinct delay of the two-way travel time (TWT) of the surface reflection during wet-snow conditions. This delay can easily be explained by the decrease in wave speed due to LWC infiltration. While comparing physically measured snow depth to TWT, Mitterer et al. (2011) were able to calculate for volumetric LWC assuming that the measured snow depth matches the snow height above the radar antennas. Additionally, they observed a distinctly pronounced diurnal/nocturnal cycle in the volumetric LWC, reproduced in surface oscillation of the radargram. In this data set, during wet-snow conditions, probed depths match exactly the picked radar snow height, which was converted to depth assuming dry-snow conditions. Furthermore, a distinct diurnal surface increase was not present as well, indicating that liquid water cannot be stored over a longer period within this slope.

3.2 *Spatial and temporal variation of snowpack properties along the tramway transect*

Figure 4 represents surface heights above ground (in TWT) of the snowpack for all 11 conducted tramway transects in 2012. Such a presentation involves 2 uncertainties for direct comparison:

(i) changes of the ground reflection (e.g. unfrozen - frozen soil, basal melt water) may influence the ground picking and thereby are reproduced in the snowpack presentation;

(ii) alternations of the wave speed among transects are not visible as only recorded TWT are presented.

However, as in the upGPR data set (Fig 2), the probed snow depth is almost exactly matching the picked surface line in April, the assumption of minor wave-speed alternations during melt season seems appropriate. In dry-snow conditions, Mitterer et al. (2011) showed that a mean wave speed for total snow-depth conversion is adequate, if the value is adapted for the seasonal bulk density. The resulting error of this assumption can be neglected.

The range of variability in TWT in Figure 4a is rather small and corresponds well with the point measurements of the upGPR (Fig. 2). There, we observed an almost parallel settlement from Feb. 2-16. Along the transects, only the first snow mound between 8–10m, recognizable for the first two February measurements, caused obvious variability. Afterwards this mound was eroded (Feb. 16), and two larger new-snow events accumulated another 0.25m of snow before the next transect (Feb 23). Again, the respective TWT-values showed parallel increases and the standard deviation (STD) of the subtraction of both measurements remained rather small (#3, Fig. 3). Another large new-snow event including settlement and melt (#5, Feb 28 – Mar 13, Fig. 3) did not change the snow-depth pattern significantly either.

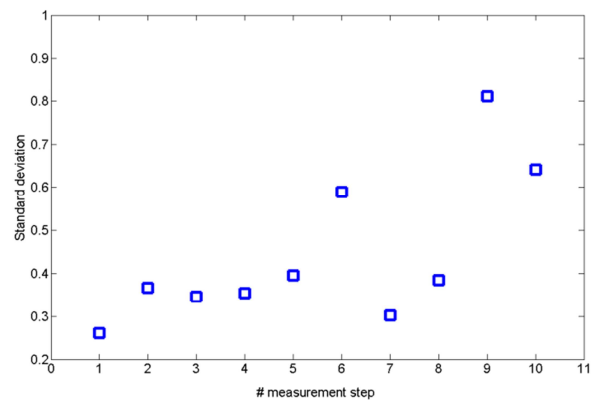


Figure 3: Standard deviation of the difference between 2 successive tramway transects: # 1: Feb 02.-Feb 09, #2: Feb 09-Feb 16, #3: Feb 16-Feb 23, #4: Feb 23-Feb 28, #5: Feb 28-Mar 13, #6: Mar 13-Mar 20, #7: Mar 20-Mar 27, #8: Mar 27-Apr03, #9: Apr 03-Apr 10, #10: Apr 10-Apr17.

However, for the week following Mar. 13, a strong increase in STD is observable (#6, Fig. 3). Within this week a strong rain-on-snow event accompanied with about 0.5m of new snow changed the

snow-depth pattern along the transect significantly. While, obviously, during the next 2 weeks melt occurred (Fig. 2), STD-values were comparable to February conditions. Only after early April, melt influenced the snow-depth pattern such that significant differences from one transect measurement

to another were detectable. We state that on this slope only rain and very pronounced melt events have a remarkable influence on the snow depth distribution along the radar transect.

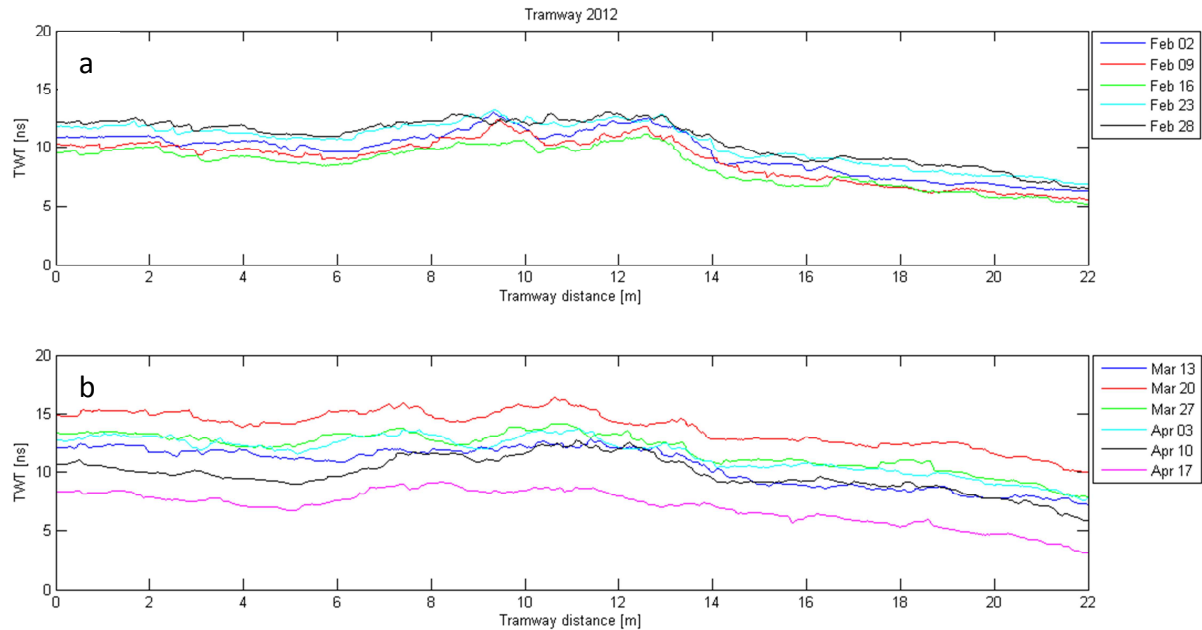


Figure 4: Display of the recorded two-way travel times of the snow depth along the respective transects. The plot (a) represents conditions in February 2012 along the tramway transect and plot (b) conditions, when melt affected the snowpack. Each color stands for one measurement during winter season 2012.

Strain was calculated in accordance to Heilig et al (2010) such that layer thicknesses at time t were subtracted by layer thicknesses at time $t+1$ for each increment and divided by an averaged thickness over t and $t+1$. Analyses in Figure 5 were performed on changes of the strain in thickness of the layer between the respective snow surface and the position of the buried former surface before March 13 (Figure 2 upper arrow). As strain for the period from Mar 27 – Apr 03 is oscillating around $S=0$ and the mean with $\mu_{S2} = 0.04$ is almost a factor of 9 smaller than for the first period ($\mu_{S1} = 0.38$) we conclude that most of the settlement for this layer took place from March 20 – 27. The point measurements at the upGPR confirm this assumption (Fig. 2). The few parts of the transect where strain for the second period is larger than for the first one, most likely, can be related to errors in the layer picking for the March 27 transect. Constructive and destructive interferences in the radar signal are likely due to a high amount of various signal occurrences above the buried surface signal (see Fig 2). In this case, upward-looking radar has

advantages compared to above-surface measurements, as the old surface signal in the upGPR did not get inferred by the stratigraphy above.

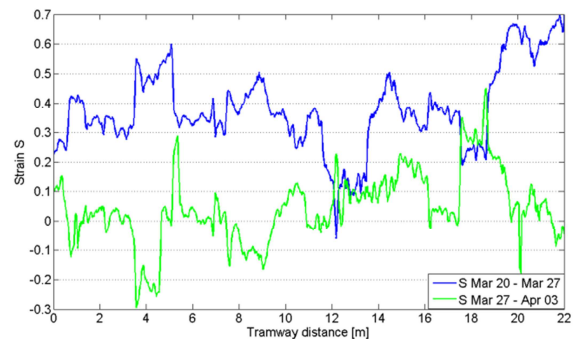


Figure 5: Strain S of the layer above the Mar 13 surface. Blue line represents the strain for the period March 20 – March 27. Green line shows strain for the period March 27 – April 03.

4. CONCLUSIONS

For the first time continuous upGPR observations at a point were successfully combined with weekly spatial measurements from an aerial tramway. The upGPR system shows promising potential for continuous monitoring of snow stratigraphy for the observed test site. Major changes in stratigraphy at this point location were followed along a 22m tramway transect as well. Significant changes in snow-depth patterns were not observed until strong melt occurrences dominated the slope. On the other hand, while accumulation dominates the pattern appears to be very homogenous. In terms of strain, the upGPR location is in a very good agreement to the whole slope. Comparison of TWT and manual depth observations indicate that this sloped site retained very little bulk liquid water, possibly due to lateral movement of water along stratigraphic boundaries.

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Author Index

Adachi, Satoru	918, 1054	Brun, Michaël	703
Adams, Edward E.	179, 186, 201, 807	Brusseau, Paul A.	786
Adler, Dorothy	516	Buhler, Ryan	84
Alig, Claudia	51	Bühler, Yves	264, 392, 420
Amano, Shigeaki	1011	Burelli, Giovanna	750
Andreassen, Dag T.	674	Buser, Othmar	32
Andreev, Leonid	134	Caccamo, Paolo	820
Angutikjuak, Illkoo	968	Camp, Tracy	487, 989
Atkins, Dale	16, 736	Campbell, Cam P.	450
Babineau-Z, Chelan	783	Campbell, Scott	165
Bailey, Rich	781	Candela, Salvatore G.	650
Bair, Edward H.	111, 923, 930	Cardu, Marilena	943
Baker, Jessica	23, 968	Carran, Ann	285
Bakkehøi, Steinar	414	Carran, Wayne	285
Barberis, Michela	528	Castlunger, Ludwig	827
Barbero, Monica	662	Ceaglio, Elisabetta	561
Barbero, Secondo	948	Chabot, Doug	62, 968, 1065
Barkhausen, John W.	348	Challender, Stuart	1040
Bartelt, Perry	32, 127, 244, 420, 591	Chambon, Guillaume	617, 644
Bartoli, Francesco	367	Chenoweth, Tucker	333
Baugher, Paul	220, 494	Cheuvront, April	968
Bebi, Peter	244, 420	Chiaia, Bernardino	277, 433, 943
Belford, Matt	23, 968	Chiambretti, Igor	723
Bellaire, Sascha	172, 194	Chiroiu, Patrick	729
Bellot, Hervé	961, 976	Christen, Marc	38, 420, 444, 591
Bennett, Tom	968	Christiansen, Hanne H.	467
Berthet-Rambaud, Philippe	134	Christie, Steve	361
Bertrand, David	703	Chrustek, Pawel	770
Bilek, Hanno	324	Clark, Jason	807
Binger, Jonathan	783	Clayton, Mary L.	513
Birkeland, Karl	62, 98, 104, 111, 269, 458	Collinson, Jim	290
.....	462, 968, 993, 1033, 1040	Conlan, Michael	55
Biskupic, Marek	324, 770	Conway, Howard	285, 866
Bjordal, Heidi	398	Covington, Chris	866
Björk, Christian	234	Crocker, Jesse F.	855
Bogie, Donald	740	Cucchi, Franco	750
Bones, Josephine	142	Custer, Stephan G.	807, 1040
Bonnand, Sheila	807	Davis, Robert E.	923, 930
Borish, Matthew J.	1040	De Biagi, Valerio	433, 662
Bourjaillat, Fanny	134	Debernardi, A	795
Bovet, Eloïse	277	Delaney, Christina M.	983
Bowker, Daniel	968	Dellavedova, Paola	541
Boyco, Alexander	134	Delparte, Donna M.	439
Boyd, Jeff	307	Diegel, Paul D.	387
Breien, Hedda	161, 633	Dixon, Mark	968
Bruendl, Michael	639, 746	Domaas, Ulrik	38
Brugger, Hermann	307, 324, 827	Dozier, Jeff	111, 923

Dreier, Lisa	603	Gleason, Andy	259
Duclos, Alain	473	Gleirscher, Engelbert	937
Dundas, Mark	375	Goddard, Penelope H.	580
Durand, Yves	46, 961, 998	Godone, Danilo	277, 948
Ebner, Isabel	827	Goetz, Daniel	998
Eck, Markus	314	Gould, Brian	450
Eckerstorfer, Markus	462, 467	Gould, Ryan R.	363
Eckert, Nicolas	644	Granhed, Magnus	16
Edgerly, Bruce	494	Granig, Matthias	444
Eisen, Olaf	599	Grant, Kim	23, 968
Ekseth, Kristine	680	Green, Sam	23, 968
Elder, Dylan	968	Greene, Ethan M.	666, 968
Elder, Kelly	968	Grêt-Regamey, Adrienne ..	244, 628
Elder, Lee	968	Grimsdottir, Harpa	161, 956
Ellevold, Jo Gunnar	693	Gromke, C	1023
Elsensohn, Fidel	307	Guttmann, Ethan	923
Etter, Hans-Juerg	746	Guy, Zach	458
Evans, Samantha	1069	Guyomarc'h, Gilbert	961, 976
Exner, Thomas	506	Haegeli, Pascal	324, 800, 859
Fagre, Daniel B.	872, 884	Haider, Wolfgang	800
Falk, Markus	324, 859	Hallandvik, Linda	775
Fallgatter, Cale J.	930	Harbitz, Carl	38
Fallon, Sean	788	Hartman, Hal	666
Farestveit, Njål	657	Harvey, Stephan	127, 603, 756
Farnsworth, Wesley R.	462, 467	Hauksson, Sigurjon	685
Fassnacht, Steven R.	666	Havens, Scott	866, 1059
Faug, Thierry	820	Hedrick, Andrew	1059
Feick, Sebastian	603	Heilig, Achim	259, 599, 1059, 1069
Feistl, Thomas	32, 420, 628	Helgaas, Ole-Andre	674
Ferraris, Stefano	561	Hellum, Oyvind S.	674
Fierz, Charles	92	Hendriks, Jordy	62, 553, 807, 872, 884, 993
Filippa, Gianluca	561, 948, 1017	1005, 1028, 1033, 1040
Finnegan, David C.	923	Henninger, Irene	1005
Fischer, Craig	23	Hervé, Bellot	622
Fischer, Jan-Thomas	444, 574, 937	Herwijnen, Alec van	104, 899
Floyer, James A.	252	Hestnes, Erik	414
Fратиanni, Simona	948	Hill, Andy	848
Frauenfelder, Regula	392, 398	Hirashima, Hiroyuki	1054
Freppaz, Michele	277, 561, 591, 795, 948	Hobman, Andrew	740
Frigo, Barbara	433, 662	Hoeller, Peter	329
Fromm, Reinhard	574	Hoffman, Scott	781
Garnero, Gabriele	948	Hopewell, Sean C.	764
Garrett, Timothy J.	930	Horender, Stefan	1023
Gauer, Peter	427, 574	Horton, Simon	194
Gaume, Johan	617, 644	Houfek, Nicholas	23, 968
Gauthier, Dave	115, 1047	Howlett, Daniel	930
Gearheard, Shari	968	Hoyer, Ian	1005
Genswein, Manuel	341, 501	Høydal, Øyvind A.	633
Genthon, Christophe	976	Huntington, Caleb	968
Giedt, Greg	968	Huntington, Henry	968
Giraud, Gerald	998	Huntington, Thomas	968

Ikeda, Shinji	121, 878	Marchetti, Emanuele	723
Ingolfsson, Orn	956	Margreth, Stefan	127, 134, 150
Iori, Maurizio	709	Marienthal, Alex	62
Issler, Dieter	38	Maris, Malou	998
Ito, Yasuhiko	121, 878	Maris, Robb	23, 968
Jackson, Jahrain	439	Marriott, Rich	807
Jamieson, Bruce	1, 55, 84, 172, 194	Marsh, Andrea	968
.....	269, 506, 716, 1047	Marshall, Hans Peter	259, 866, 968, 1059, 1069
Janes, Mike	294	Marty, Christoph	244
Janjigian, Dan	23, 968	Matsushita, Hiroki	696, 878
Jarry, Frederic	324, 341	Matsuzawa, Masaru	696, 878
Johnson, Crane	968	Mattice, Tom	150
Johnson, Jerry	768	McCabe, Doug	1005
Jones, Alan S.	1	McClung, David	256
Jonsson, Arni	680, 685	McDouall, Joanna	834, 840
Jonsson, Magni H.	161, 956	McGhan, Debra	516
Katushima, Takafumi	121	McNeally, Phoebe B.	290
Kellam, Janet	9	Mears, Art	294
Kern, Martin	937	Meier, Lorenz	756
King, Rebekah L.	689	Meiners, Aidan	23, 968
Klassen, Karl	165, 209, 859	Meiners, Alex	968
Knutson, Tracey L.	227	Meiners, Theo	23, 968
Kogelnig, Arnold	535	Milford Team, The.	285
Koh, Gary	259	Miller, Dan	142, 179, 186, 408, 1033
Koschuk, Richard	535	Miller, Tamara	807
Kose, Katsumi	918	Mitchell, Christina	834, 840
Kraft, Maggi	1028	Mitterer, Christoph	51, 77, 599, 603, 610
Kristensen, Ida S.	497	Monti, Fabiano	92
Kristensen, Krister	161, 414, 497, 501	Morin, Chris	240
Kroell, Franz	353	Morris, Merletta	516
Kronholm, Kalle	38, 693	Murphy, Matt	553
Kyzek, Filip	770	Murphy, Miranda	523
Lambert, Richard	149	Naaïm-Bouvet, Florence	961, 976
Langeland, Stian	775	Naaïm, Mohamed	617, 622, 644, 703
Larsen, Siri Ø.	398	Nakamura, Hiroshi	696, 878
Lato, Matthew J.	392	Newby, James	450
Latosuo, Eeva	786, 788	Nicholson, Bill	866
LeBaron, Anthony M.	408	Nishimura, Kouichi	976
Lehning, Michael	569, 1023	Noro, Tomoyuki	121, 586
Leonard, Tom	1005	Onaca, Alexandru	729
Létang, Dominique	341	Onslow, Terry	553
Levy, Brandon	904	Ousset, Frederic	622, 820
LeWinter, Adam L.	923	Ousset, Isabelle	703
Limam, Ali	703	Ozeki, Toshihiro	918
Liston, Glen	968	Øvrebotten, Vetle Aase	775
Lizuch, Milan	770	Paal, Peter	307
Logan, Spencer	324, 479	Palermo, Cyril	976
Lovejoy, David W.	814	Palluq, Limakee	968
Maggioni, Margherita	277, 591, 795, 1017	Paulsen, Eivind M.	680
Maki, Katuhiro	1011	Payen, Valentin	998
Maleski, Pete	62	Peitzsch, Erich H.	872, 884

Perkins, John D.	439	Sovilla, Betty	541, 569, 574
Peter, Dirninger	831	Staffler, Hanspeter	827
Peterson, Michael	439	Stanford, Mike P.	904
Petri, Peter	375	Stanton, Brad T.	179
Pielmeier, Christine	127	Staron, Patrick	186
Pitet, Luca	541, 795	Starr, Banning	968
Podolskiy, Evgeny A.	617	Statham, Grant	165
Pope, Josh	23, 968	Steiner, Richard W.	375
Preindl, Anton	827	Steinkogler, Walter	32, 444, 569
Procter, Emily	770, 827	Stelzer, Gernot	937
Prokop, Alexander	831, 961	Stimberis, John	547
Qillaq, Esa	968	Stohlgren, Thomas J.	666
Rainer, Elisabeth	937	Storm, Ilya	892, 908
Rammer, Lambert	937	Strapazzon, Giacomo	307, 827
Rapin, Francois	149, 707, 708	Strong-Cvetich, Luke	800
Ravanat, Xavier	622, 820	Stucki, Thomas	127
Raviglione, Massimo	528, 709	Stuefer, Svetlana	934
Reuter, Benjamin	28	Sturm, Matthew	259, 934
Richnavsk, Jozef	770	Syre, Egil	680
Ripepe, Maurizio	723	Takeuchi, Yukari	121
Rivella, Enrico	948	Techel, Frank	234
Rubin, Marc J.	487, 989	Teich, Michaela	244, 420, 628
Rust, Michael	314	Terzago, Silvia	948
Sakakibara, Ken-Ichi	1011	Thibert, Emmanuel	622
Salberg, Arnt-Børre	398	Thumlert, Scott	506
Sanders, AJ	23	Toepfer, Scott	666
Sanguya, Joelli	968	Tracz, Dave	55
Sato, Atsushi	1054	Tremper, Bruce	387
Saurer, Mark E.	69	Trombetta, Mike	23
Savage, Scott	142, 768	Trover, Randy	290
Scarpato, David J.	300	Tyler, Roger	968
Schmid, Lino	599	Ulivieri, Giacomo	723
Schober, Michael	314	Ulrich, Melanie	244
Schory, Peter	290	Uttl, Bob	834, 840
Schweizer, Jürg	28, 51, 77, 92, 341	Vallée, Thierry	381
.....	599, 603, 610, 756	Vallier, Jean-Luc	134
Seebacher, Florian	827	van den Tillaar, Roland	775
Segor, Valerio	541, 561, 723, 750, 795	van Herwijnen, Alec	98, 111, 408, 989
Sehnert, Sam	23, 968	Vassella, Irene	628
Sharp, Eirik A.	214, 892	Vera, Cesar	32
Shea, Cora	269	Vionnet, Vincent	961
Shkurko, Konstantin	930	Voiculescu, Mircea	729
Simenhois, Ron	104, 111, 899, 968	Wagner, Wendy	913
Simonson, Sara E.	666	Waller, Scott	848
Sinickas, Alexandra	716	Walter, Benjamin A.	1023
Skjøstad, Magnus Berger	775	Walters, David J.	201
Skutlaberg, Sara	657	Welch, Kristina	404
Slaughter, Andrew E.	395	Werner, Munter	501
Smebye, Helge C.	680	Wever, Nander	1023
Smith, Michael A.	214, 892	White, Carmela	834
Solberg, Rune	398	Wiegele, Mike	157

Wieland, Matt	993, 1028
Wilbur, Chris	294
Willy, Dick	848
Winstral, Adam	1059
Winterberger, Eveline	307
Witmer, Frank	479
Woodard, Martin J.	300
Wooldridge, Robyn	1033
Wright, Kevin	333
Wyssen, Samuel	535
Yamaguchi, Satoru	918, 1054
Yamakawa, Kimiko	1011
Young, Scott	807
Zabaras, Nicholas	395
Zafren, Ken	307
Zanini, Ermanno	561, 591, 795
iak, Igor	770
Zurbriggen, Natalie	244
Zweifel, Benjamin	234, 324

