IMF'S CONTROL OF QUASI-PERIODIC ELF-VLF EMISSIONS

Kiyohumi YUMOTO[1] and Natsuo SATO[2]

[1] *Onagawa Magnetic Observatory and Geophysical Institute,*
Tohoku University, Sendai 980
[2] *National Institute of Polar Research, 9-10, Kaga 1-chome,*
Itabashi-ku, Tokyo 173

Abstract: Correlations among the magnitude of the interplanetary magnetic field (IMF), the modulation frequency of quasi-periodic (QP) ELF-VLF emissions observed at high-latitude conjugate-pair stations, Syowa Station ($L \sim 6.1$) in Antarctica and Husafell in Iceland, and the dominant frequency of low-latitude Pc 3 magnetic pulsations observed at Hermanus ($L \sim 1.8$) located near the Syowa Station's meridian in South Africa are examined by using the data obtained during the conjugate campaign in 1977. The analysis shows that the modulation frequency of type 1 QP emissions, QP's associated with Pc 3 magnetic pulsations, is correlated well with the IMF magnitude. On the other hand, it has been recently established that the frequency of compressional Pc 3 waves in the magnetosphere is also controlled by the IMF magnitude. These observational results support the phenomenological model that compressional magnetic waves originating upstream of the earth's foreshock modulate the type 1 QP emissions near the equatorial plane in the outer magnetosphere.

1. Introduction

ELF-VLF radio noise bursts with quasi-periodic intensity modulation in the magnetosphere are known as quasi-periodic (QP) ELF-VLF emissions (HELLIWELL, 1965; KITAMURA *et al.*, 1969; SATO *et al.*, 1974). It was revealed by SATO *et al.* (1974) that QP emissions with a period of 10–150 s can be classified into two types, type 1 and type 2 QP emissions, according to whether the emissions are clearly associated with magnetic pulsations or not. CORNILLEAU-WEHRLIN *et al.* (1978) demonstrated that QP emissions were observed simultaneously on board GEOS 1 in the magnetosphere and near the geomagnetical conjugate points on the ground. SATO *et al.* (1980) and SATO and KOKUBUN (1980) indicated that QP emissions were observed at conjugate-pair stations, Syowa Station in Antarctica and Husafell in Iceland. It is also found that the type 1 QP emissions are generally more correlated with the D component of magnetic pulsations, suggesting that the type 1 QP emissions are generated near the equatorial plane in the outer magnetosphere and then propagate simultaneously to both hemispheres along the field line of force. By using the f-t spectra of a few hundred QP events observed at high latitudes, SATO and FUKUNISHI (1981) proposed two phenomenological models to explain the f-t spectra, *i.e.*, the non-dispersive type of QP emissions is generated by standing oscillations of the magnetic field lines which have effective compressional components, while the rising tone type is generated by compressional Pc 3 magnetic pulsations which propagate in a radial direction toward the earth.

On the other hand, YUMOTO and SAITO (1983) recently found that compressional Pc 3–4 magnetic pulsations are observed at geosynchronous orbit in the magnetosphere. Amplitudes of the compressional Pc 3–4 waves detected at GEOS 2 are smaller than those of transverse Pc 4–5 oscillations, but sufficiently large to be a source of daytime low-latitude Pc 3–4 pulsations on the ground. YUMOTO *et al.* (1984, 1985a, b) examined the correlations among the IMF intensity (B_{IMF}) and the dominant frequencies (f) of the compressional Pc 3–4 waves at GOES 2 and daytime Pc 3–4 pulsations simultaneously observed on the ground. They suggested that the magnetosonic upstream waves, of which frequency is related to the ion cyclotron frequency and thus to the IMF magnitude in the earth's foreshock, are convected to the magnetopause through the magnetosheath, having been transmitted into the magnetosphere and then observed as the propagating compressional Pc 3–4 waves in the outer magnetosphere. The correlation between B_{IMF} and f of the compressional Pc 3–4 waves in the magnetosphere indicates a relation of $f\,(\mathrm{mHz}) \sim 6.0 \times B_{\mathrm{IMF}}\,(\mathrm{nT})$, which is in agreement with those obtained by the ground data (see reviews of GREEN *et al.*, 1983) and the satellite data (RUSSELL and HOPPE, 1981).

In this paper we examine the relationships among the intensity of the IMF, the modulation frequency of QP emissions observed at conjugate-pair stations, Syowa in Antarctica and Husafell in Iceland ($L \sim 6.1$), and the dominant frequency of Pc 3–4 magnetic pulsations observed at Hermanus, South Africa ($L \sim 1.8$).

2. Observation

SATO *et al.* (1980) summarized QP emission events observed at conjugate-pair stations, Syowa Station (66.1°S, 70.8°W in the invariant geomagnetic coordinates, $L \sim 6.1$) in Antarctica and Husafell (66.0°N, 70.2°W, $L \sim 6.1$) in Iceland during the period from July 31 to September 17, 1977. We have examined the relationships among the modulation period of QP emissions and Pc 3 magnetic pulsations observed at the conjugate-pair stations (listed in Table 2 of SATO *et al.*, 1980), the hourly values of the total strength of the IMF obtained from the NSSDC Interplanetary Medium Data Book (KING, 1979), and the frequency of low-latitude Pc 3 pulsation at Hermanus (43.1°S, 81.1°W, $L \sim 1.8$) in South Africa. Hermanus is located near the same geomagnetic meridian as Syowa Station. The spectral analysis to determine the modulation frequency of QP emissions at the high-latitude conjugate stations was done by the use of the conversational analysis program (CSAP) system (IWABUCHI *et al.*, 1978). The details of the procedure are given by SATO and KOKUBUN (1980). Pulsation frequencies in the Pc 3 range at the low latitude (Hermanus) during the same interval of the QP events at Syowa and Husafell are obtained by hand scaling of the mean dominant pulsation frequencies. If two of three equally distinct frequencies of Pc 3 pulsations were present during the QP events, they were all noted. It is appreciated that this subjective hand scaling method can be open to the errors and bias in that the eye is inevitably drawn to the clearest sinusoidal events. However, Pc 3 activities at Hermanus were sufficiently visible on the induction magnetograms whenever the QP

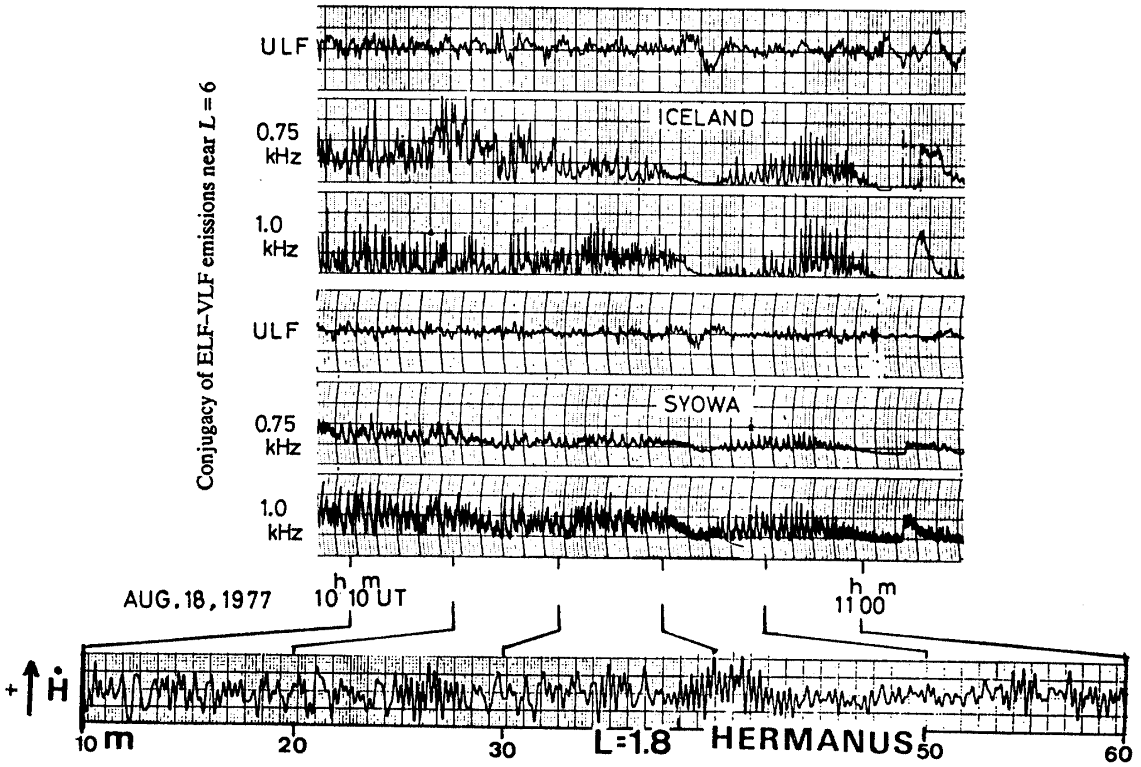

Fig. 1. An example of simultaneous records of the H component of magnetic pulsations, type 1 QP emissions in the frequency bands of 0.75 and 1.0 kHz observed at conjugate-pair stations, Syowa and Husafell (L=6.1), and the H component of magnetic pulsations observed at Hermanus (L=1.8) in the time interval of 1010–1110 UT on August 18, 1977.

emissions at Syowa and Husafell had been observed as shown in Fig. 1, and the data set would still be representative of Pc 3 frequency at the low latitude.

Figure 1 shows a representative example of simultaneous records of the *H* component of magnetic pulsations and type 1 QP emissions in the frequency bands of 0.75 and 1.0 kHz at the conjugate-pair stations and the *H* component of magnetic pulsations at Hermanus in the time interval of 1010–1110 UT on August 18, 1977. It is evident that QP emissions and Pc 3 magnetic pulsations simultaneously occur at the conjugate-pair stations. The dominant frequencies of both the QP emissions and the Pc 3 magnetic pulsations are found around 25–50 mHz (see Table 2 of SATO *et al.*, 1980). The low-latitude Pc 3 pulsations are also activated during the time interval, although, it is difficult to identify the one-to-one correspondence between the low-latitude Pc 3 pulsations and the high-latitude Pc 3 pulsations. The dominant frequencies of the low-latitude Pc 3 pulsations are found to be 23 and 67 mHz, which are slightly different from the frequencies of the QP emissions and the high-latitude Pc 3 pulsations.

Figure 2 shows scatter plots of the modulation frequency (f) of type 1 QP emissions observed at the conjugate-pair stations against the IMF magnitude (B_{IMF}) (see the list in Table 2 of SATO *et al.*, 1980). The thin line indicates the relation of $f(\mathrm{mHz})=6.0\times B_{\mathrm{IMF}}$ (nT). The thick lines represent the ranges from higher to lower modulation frequencies of the QP emission events. It is clearly found that the modu-

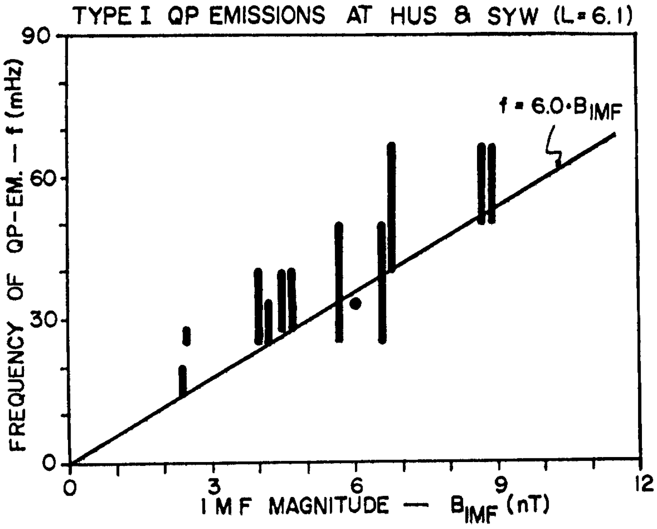

Fig. 2. Scatter plots of the modulated frequency (f) *of type 1 QP emissions observed at the high-latitude conjugate stations against the IMF magnitude* (B_{IMF})*. The thin line indicates the relation of* f (mHz) $=6.0\times B_{\mathrm{IMF}}$ (nT)*, and the thick line represents the frequency range of each QP event.*

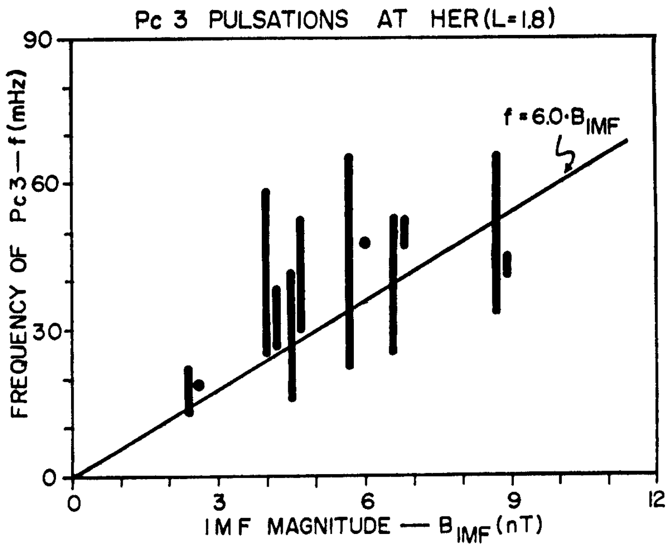

Fig. 3. The same as Fig. 2 except the dominant frequency (f) *of low-latitude Pc 3 pulsations against the IMF magnitude* (B_{IMF})*.*

lation frequency of the type 1 QP emissions is correlated with the IMF magnitude. Figure 3 shows the same plots as Fig. 2 except the dominant frequency (f) of low-latitude Pc 3 pulsations against the IMF magnitude (B_{IMF}). The thick lines represent the range from higher to lower dominant frequencies, which are obtained by hand scaling of the mean pulsations frequency of Pc 3 magnetic pulsations at Hermanus. It is evident that the low-latitude Pc 3 pulsations are more scattered against B_{IMF} than those of the type 1 QP emissions as shown in Fig. 2. The modulation periods of the type 1 QP emissions are found to be more strongly controlled by the IMF mag-

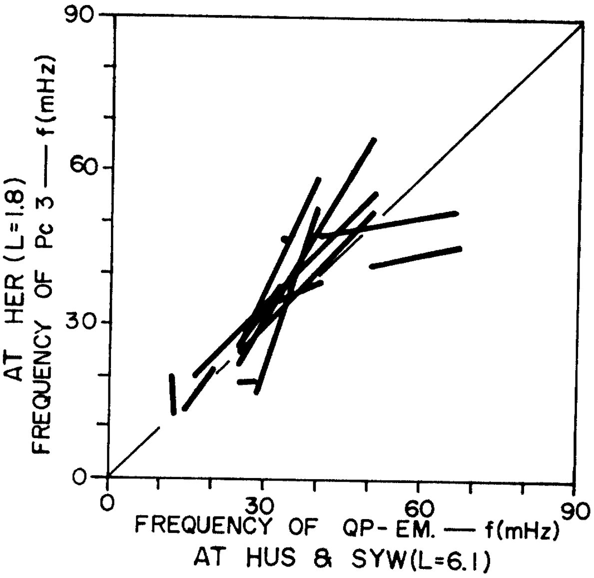

Fig. 4. Scatter plots of the modulation frequency of the type 1 QP emissions observed at the high-latitude conjugate-pair stations against the frequency of the low-latitude Pc 3 magnetic pulsations observed during the same interval of the QP events.

nitude than those of the low-latitude Pc 3 pulsations.

The relation between the modulation frequency of the type 1 QP emission observed at the high latitude and the dominant frequency of the low-latitude Pc 3 pulsations observed during the same time interval of the QP events is shown in Fig. 4. It is found that there is a weak correlation between these phenomena.

3. Summary and Discussions

Findings which were obtained from the present data analysis are summarized as follows:

(1) The modulation frequencies of type 1 QP emissions observed at high latitudes (Syowa and Husafell; $L\sim 6.1$) are correlated with the IMF magnitude. (2) The frequencies of low-latitude Pc 3 pulsations observed at Hermanus ($L\sim 1.8$) during the same time interval of the type 1 QP events are more weakly correlated with the IMF magnitude. (3) The low-latitude Pc 3 pulsations tend to have similar periods to the type 1 QP emissions at the high-latitudes, but one-to-one correspondence between those phenomena could not be found.

A phenomenological model to explain the f–t spectra of QP emissions was proposed by SATO and FUKUNISHI (1981). According to their model, the rising tone type of QP emissions is generated by compressional Pc 3 magnetic pulsations which propagate in a radial direction toward the earth, while the non-dispersive type is explained by an effective compressional component of standing HM waves along the magnetic field lines. Since the modulation frequency of QP emissions correlated with the IMF magnitude (see Fig. 2) cannot be explained by the dominant frequency of the standing oscillations determined mainly by local plasma parameters in the magnetosphere, we propose another candidate of the non-dispersive type QP emissions. Whenever compressional Pc 3 waves originating outside the magnetosphere are trapped in the radial direction in the trough between the two peaks of Alfvén speed, *e.g.*, in the detached plasma region and/or the plasma island in the outer magnetosphere (*cf.* YUMOTO and SAITO, 1983), intensity fluctuations of the trapped compressional Pc 3 waves in the Alfvén trough can also modulate the intensity of ELF-VLF emissions near the magnetic equator.

On the other hand, frequencies of compressional Pc 3–4 waves in the magnetosphere are demonstrated to be well correlated with the IMF magnitude (YUMOTO *et al.*, 1984, 1985a, b). The magnetosonic upstream waves, having a finite frequency bandwidth can be excited by the well-known anomalous ion cyclotron instability driven by the reflected ion beam in the earth's foreshock and thus related to both the IMF magnitude and the energy range of the reflected ion beam. The magnetosonic upstream waves were concluded to be transmitted across the magnetosheath and the magnetopause without a significant change in spectra, and then observed as the compressional Pc 3–4 waves in the outer magnetosphere. The type 1 QP emissions correlated with the IMF magnitude (Fig. 2) are believed to be modulated by the compressional Pc 3 waves originating in the upstream region of the earth's foreshock. The difference of the *f-t* spectra, the rising tone type or the non-dispersive type of the type 1 QP emissions, can be interpreted by the different mechanisms of wave propagation, *i.e.*, propagating mode or trapping mode, of the compressional Pc 3 waves in the magnetosphere.

Because the correlation between frequencies of high-latitude Pc 3 magnetic pulsations at College ($L=5.6$) and those of low-latitude Pc 3 pulsations at Ewa Beach ($L=1.15$), which is located near the College's meridian, is not higher. YUMOTO *et al.* (1985a) recently speculated that the high-latitude Pc 3–4 pulsations localized in the auroral zone cannot propagate into low latitudes through the wave guide formed by the bottom of the ionosphere and the layer of maximum Alfvén velocity at 2000 km from the surface of the earth (JACOBS and WATANABE, 1962). They concluded that low-latitude Pc 3 magnetic pulsations are composed of various hydromagnetic oscillations coupled with the compressional Pc 3 waves in the magnetosphere (YUMOTO and SAITO, 1983). The dominant frequencies of the various HM oscillations at different locations in the inner magnetosphere are in general determined by the local magnetic field and plasma density (SINGER *et al.*, 1981; TAKAHASHI and MCPHERRON, 1982; YUMOTO and SAITO, 1983). Therefore, the lower correlation between the IMF magnitude and the low-latitude Pc 3 frequencies as shown in Fig. 3 can be interpreted as a superposition of the dominant frequencies of the compressional Pc 3 source waves in the magnetosphere and the coupled resonance oscillations in the inner magnetosphere.

We can construct a scenario on the propagation mechanism of compressional Pc 3 originating in the earth's foreshock as follows: The transmitted compressional upstream waves, which propagate in the radial direction toward the earth, can modulate the intensity of ELF-VLF emissions near the magnetic equator in the outer magnetosphere. The types of the modulation frequency are believed to depend on the development of the Alfvén trough in the outer magnetosphere. The propagating compressional Pc 3 waves can generate the rising tone type of the type 1 QP emissions, while the trapping compressional Pc 3 waves in the Alfvén trough can generate the non-dispersive type QP emissions. The propagating compressional Pc 3 waves in the outer magnetosphere are transmitted into the plasmasphere, and then couple with various HM oscillations at different locations in the inner magnetosphere. The coupled HM oscillation in the Pc 3 frequency range has a different dominant frequency, which is determined mainly by the local magnetic field and plasma density. Therefore, it would be difficult to determine the one-to-one correspondence between the modulation frequency of QP emissions observed at high latitudes and the dominant frequency of low-latitude Pc 3 magnetic pulsations.

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References

CARSON, W. B., KOCH, J. A. and GALLET, R. M. (1965): Long period very low frequency emissions. J. Geophys. Res., **70**, 4293–4303.

CORNILLEAU-WEHRLIN, N., GENDRIN, R. and TIXIER, M. (1978): VLF waves; Conjugated ground-satellite relationships. Space Sci. Rev., **22**, 419–431.

GREEN, C. A., ODERA, T. J. and STUART, W. F. (1983): The relationship between strength of the IMF and the frequency of magnetic pulsations on the ground and in the solar wind. Planet. Space Sci., **31**, 559–567.

HELLIWELL, R. A. (1965): Whistlers and Related Ionospheric Phenomena. Stanford, Stanford Univ. Press, 349 p.

IWABUCHI, M., FUJII, R. and UTSUMI, T. (1978): Gurafikku disupurei o mochi ita kaiwagata supekutoru kaiseki sisutemu (Conversational system of spectrum analysis by the use of geographic display). Nankyoku Shiryô (Antarct. Rec.), **62**, 29–70.

JACOBS, J. A. and WATANABE, T. (1962): Propagation of hydromagnetic waves in the lower exosphere and the origin of short period geomagnetic micropulsations. J. Atmos. Terr. Phys., **24**, 413–434.

KING, J. H. (1979): Interplanetary medium data book supplement 1, 1975–1978. NSSDC, NASA.

KITAMURA, T., JACOBS, J. A., WATANABE, T. and FLINT, R. B., Jr. (1969): An investigation of quasi-periodic VLF emissions. J. Geophys. Res., **74**, 5652–5664.

RUSELL, C. T. and HOPPE, M. M. (1981): The dependence of upstream wave periods on the interplanetary magnetic field strength. Geophys. Res. Lett., **8**, 615–617.

SATO, N. and FUKUNISHI, H. (1981): Interaction between ELF-VLF emissions and magnetic pulsations; Classification of quasi-periodic ELF-VLF emissions based on frequency-time spectra. J. Geophys. Res., **86**, 19–29.

SATO, N. and KOKUBUN, S. (1980): Interaction between ELF-VLF emissions and magnetic pulsations: Quasi-period ELF-VLF emissions associated with Pc 3–4 magnetic pulsations and their geomagnetic conjugacy. J. Geophys. Res., **85**, 101–113.

SATO, N., AYUKAWA, M. and FUKUNISHI, H. (1980): Conjugacy of ELF-VLF emissions near $L=6$. J. Atmos. Terr. Phys., **42**, 911–928.

SATO, N., HAYASHI, K., KOKUBUN, S., OGUTI, T. and FUKUNISHI, H. (1974): Relationships between quasi-periodic VLF emissions and geomagnetic pulsations. J. Atmos. Terr. Phys., **36**, 1515–

1526.

SINGER, H. J., SOUTHWOOD, D. J., WALKER, R. J. and KIVELSON, M. G. (1981): Alfvén wave resonances in realistic magnetospheric magnetic field geometry. J. Geophys. Res., **86**, 4589–4596.

TAKAHASHI, K. and MCPHERRON, R. L. (1982): Harmonic structure of Pc 3–4 magnetic pulsations. J. Geophys. Res., **87**, 1504–1516.

YUMOTO, K. and SAITO, T. (1983): Relation of compressional HM waves at GOES 2 to low-latitude Pc 3 magnetic pulsations. J. Geophys. Res., **88**, 10041–10052.

YUMOTO, K., SAITO, T., TSURUTANI, B. T., SMITH, E. J. and AKASOFU, S.-I. (1984): Relationship between the IMF magnitude and Pc 3 magnetic pulsations in the magnetosphere. J. Geophys. Res., **89**, 9731–9740.

YUMOTO, K., SAITO, T., AKASOFU, S.-I., TSURUTANI, B. T. and SMITH, E. J. (1985a): Propagation mechanism of daytime Pc 3–4 pulsations observed at synchronous orbit and multiple ground-based stations. J. Geophys. Res., **90**, 6439.

YUMOTO, K., SAITO, T., TSURUTANI, B. T., SMITH, E. J. and AKASOFU, S.-I. (1985b): Effects of the interplanetary magnetic field on the characteristics of Pc 3–4 pulsations at globally coordinated stations. Mem. Natl Inst. Polar Res., Spec. Issue, **36**, 15–26.

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