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Limits to Ice Thickness in Iowa During the Late Wisconsinan

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Minimum and maximum limits to Des Moines Lobe ice thickness in Iowa during the Late Wisconsinan glaciation are calculated. These limits are based on minimum and maximum ice thickness calculations for the Des Moines Lobe in eastern North Dakota using crustal depression indicated by Lake Agassiz strandlines. Minimum and maximum basal shear stresses for the Des Moines Lobe are calculated by projecting a flow line from the terminus of the Des Moines Lobe back up-ice to the study site in northeastern North Dakota. Ice thickness in Iowa is then calculated with a method that uses the basal shear stress values. The ice thickness limits calculated in this study assume that 1) post-glacial rebound in North Dakota is complete, 2) restrained rebound in eastern North Dakota did not exceed 73%, 3) basal shear stress controlled ice thickness in the marginal portions of the Laurentide Ice Sheet, and 4) the pore water pressure in the basal till of the reconstructed ice sheet was very close to the glaciostatic pressure. Ice thickness is calculated at between 131 and 484 m at the Iowa-Minnesota border. The results of this study are then compared to results from other Des Moines Lobe ice thickness studies.

The Des Moines Lobe ice in north central Iowa was once believed to be much thicker than current estimates. For example, Sugden (1977) depicted ice as being about 2,000 m thick and Hughes (1985) about 1,600 to 1,800 m thick in the vicinity of the Iowa-Minnesota border. In contrast, Clark (1992), Mathews (1974), Peltier (1994), and Clark et al. (1996) interpreted ice thicknesses of no more than about 700 m for the Des Moines Lobe in the vicinity of the Iowa-Minnesota border, and Boulton et al. (1985) depicted ice as being about 250 to 900 m thick in the vicinity of the Iowa-Minnesota border. The wide range of ice thickness values offered in the literature suggests that additional studies in this area are warranted.

One problem with the interpretation of thin ice along the margins of the Laurentide Ice Sheet is that this interpretation can not be tested by comparison with any modern ice sheets on the scale of the Laurentide Ice Sheet. However, ice along the margins of the Laurentide Ice Sheet is believed to have been relatively thin because of the soft, deformable sediments and poorly consolidated rocks over which the ice flowed (Boulton and Jones 1979, Clark 1992, Clark 1994, Hicock and Dreimanis 1992, Clark et al. 1996), and the interpretation of thin ice on a deformable bed is supported by several lines of indirect evidence. For example, the rapid retreat that occurred along the margins of the Laurentide Ice Sheet at the end of the Wisconsinan (Dyke and Prest 1987, Andres 1973, Wright et al. 1973, Bryson et al. 1969, Wright and Ruhe 1965), rapid fluctuations of the ice margins where they were over deformable sediments (Clatk 1994, Johnson and Hansel 1990), and the lobate form of parts of the ice sheet that rested on deformable sediments (Clark 1994, Boulton and Jones 1979) are all indicative of thin ice. Deformation features and fabrics preserved in some tills (Hicock and Dreimanis 1992) and computer models of subglacial sediment transport (Alley 1991) also support the theory of thin ice on a deformable bed along the margins of the Laurentide Ice Sheet, as does a study of longitudinal shear ridges carried out by Bluemle et al. (1993) and a study of tilted Lake Agassiz strandlines in eastern North Dakota (Brevik and Reid in press, Brevik 1994). Patterson (1997) has concluded that landforms mapped in southern Minnesota indicate that the Des Moines Lobe was composed of relatively thin ice over a soft bed. Therefore, while modern comparisons with like-scaled ice sheets are not possible, abundant evidence for thin ice along the margins of the Laurentide Ice Sheet, including the Des Moines Lobe in Iowa, exists.

Brevik and Reid (in press) used crustal depression caused by the weight of the Laurentide Ice Sheet, as indicated by the Lake Agassiz Herman strandline, to calculate ice thickness limits for the point where the Herman strandline crosses the North Dakota–Canada border. This study expands on the work of Brevik and Reid (in press), combining it with a method published by Beget (1986) to calculate minimum and maximum ice sheet profiles for the Des Moines Lobe in central Iowa during the late Wisconsinan. The ice thickness limits calculated here are then compared to other published ice thickness values for central Iowa.

METHODS

Brevik and Reid (in press) used post-glacial rebound, as indicated by Lake Agassiz strandlines, to calculate minimum and maximum limits to Late Wisconsinan ice thickness of between 250 and 920 m in northeastern North Dakota. As a check on their ice thickness model, they calculated the basal stresses indicated by their ice thickness limits and compared them to basal shear stresses calculated by other researchers for the Des Moines Lobe. The basal shear stress calculations were made along a flow line projected from the terminus of the Des Moines Lobe back up-ice to the study site in eastern North Dakota (Brevik and Reid in press). The basal shear stresses calculated by Brevik and Reid (in press) were found to agree well with other published basal shear stress values, and can be used to estimate limits to ice thickness in the Iowa portion of the Des Moines Lobe during the late Wisconsinan.

The primary factor controlling ice thickness in the marginal lobes of the Laurentide Ice Sheet was the shear strength of the basal sediments (Clark et al. 1996, Clark 1994, Clark 1992, Beget 1987, Beget 1986, Clayton et al. 1985, Mathews 1974). If basal shear stress is known, ice thickness can be calculated using:

$$H = (2\tau_b L/\rho_i g)^{1/2} \qquad (1)$$

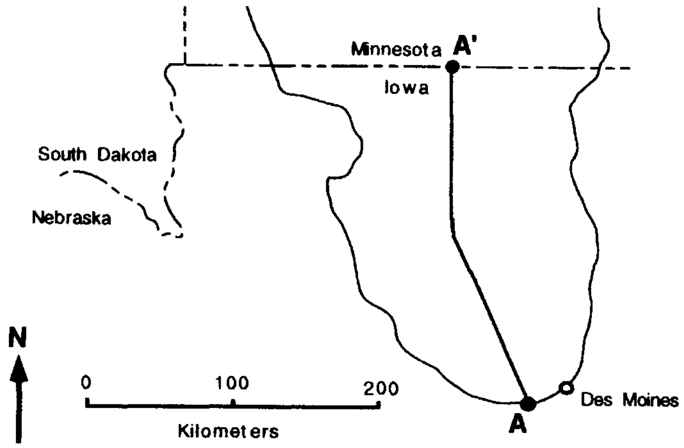

Fig. 1. Location of the Des Moines Lobe in Iowa. Ice profile reconstructions are along line A-A'. References to ice thickness at the Iowa-Minnesota border in the text refer to point A'.

where H is ice thickness, τ_b is basal shear stress, L is the distance from the glacial terminus, ρ_i is the density of ice, and g is gravitational acceleration (Beget 1986). This assumes that the pore water pressure in the basal till of the reconstructed ice sheet was close to the glaciostatic pressure, the yield strength of the basal till was lower than that of ice, and the glacier profile and flow was essentially adjusted to the yield strength of the subglacial sediment (Beget 1986). These assumptions and their validity are discussed in more detail in Beget (1986).

Brevik and Reid (in press) have calculated basal shear stresses of between 0.32 and 4.4 kPa for the Des Moines Lobe during the late Wisconsinan. The value used for the density of glacial ice is 900 kg/m^3 (Sugden and John 1976). The distance from the glacial terminus to the Minnesota border is 235 km following the approximate flow line marked A-A' on Figure 1. Ice thicknesses are calculated every 10 km for the first 110 km from the terminus, then every 25 km to the Iowa-Minnesota border. This is done because ice thickness changed more rapidly close to the terminus, so the 10 km spacing in that area does a better job of showing the ice sheet's profile than a wider spacing would.

RESULTS AND DISCUSSION

Results of this Study

The basal shear stresses from Brevik and Reid (in press) were calculated from estimates of minimum and maximum limits to ice thickness in eastern North Dakota during the late Wisconsinan. Using Equation 1 and the shear stress values given above, minimum and maximum ice thickness profiles for the Des Moines Lobe in north central Iowa were calculated (Figure 2). The thickest ice in Iowa was at the Iowa-Minnesota border, and was between 131 and 484 m thick.

Validity of the Calculated Limits

Several assumptions must hold true for the ice thickness limits calculated in this study to be valid. The ice thickness limits calculated for eastern North Dakota by Brevik and Reid (in press) assume that post-glacial rebound in eastern North Dakota is complete. Brevik and Reid (in press) also assumed that restrained rebound in eastern North Dakota did not exceed 73%. These assumptions and why they are considered to be valid are discussed in detail in Brevik and Reid (in press). This study also assumes that basal shear strength controlled ice thickness in the marginal portions of the Laurentide Ice Sheet. This assumption seems reasonable, given the number of researchers who support it (e.g. Clark et al. 1996, Clark 1994, Clark 1992, Beget 1987, Beget 1986, Clayton et al. 1985, Boulton et al. 1985, Hughes 1985, Boulton and Jones 1979, Mathews 1974). The assumptions crucial to the use of Equation 1 are discussed above, and a more detailed discussion of these assumptions can be found in Beget (1986).

Comparison to Previous Studies

Mathews (1974) published an equation that allows calculation of the ice thickness profile for an ice lobe as a function of distance from the terminus:

$$H = Ax^{1/2} \tag{2}$$

where x is the distance from the glacial terminus and A is a coefficient that varies for each given ice lobe. Mathews (1974) used moraine elevations to calculate the value of A for a number of lobes along the southern edge of the Laurentide Ice Sheet. He determined that the value of A for the Des Moines Lobe was 0.46 m$^{1/2}$. Brevik (1994) independently calculated a value of A using different points along the Bemis moraine and also arrived at a value of 0.46 m$^{1/2}$ for A on the Des Moines Lobe. The profile for the Des Moines Lobe from its terminus to the Iowa-Minnesota border produced using Mathews' (1974) method is given on Figure 2. Mathews' (1974) method gives an ice sheet profile that falls within the ice thickness limits calculated in this study (Figure 2) and results in a predicted ice thickness of 223 m at the Iowa-Minnesota border.

Clark (1992) reconstructed the surface form of the southern margins of the Laurentide Ice Sheet using moraine elevations and ice flow indicators. Clark's (1992) work did not result in an equation to reconstruct ice thickness, but did produce several ice sheet profiles, including one for the Des Moines Lobe. Clark's (1992) profile for the Des Moines Lobe (from Figure 5C, Clark 1992) is reconstructed on Figure 2. The Des Moines Lobe profile generated by Clark (1992) is essentially identical to the one calculated using Mathews' (1974) method and is within the ice thickness limits calculated in this study (Figure 2). Clark's (1992) profile predicts an ice thickness of approximately 230 m at the Iowa-Minnesota border.

Clark et al. (1996), Peltier (1994), Boulton et al. (1985), Hughes (1985), and Sugden (1977) all conducted ice thickness studies that included the Des Moines Lobe. Sugden (1977), Boulton et al. (1985), and Clark et al. (1996) reconstructed the Laurentide Ice Sheet. Sugden depicted ice thickness in the vicinity of the Iowa-Minnesota border at approximately 2000 m (estimated from Figure 2, Sugden 1977), or about four times thicker than the maximum ice thickness value calculated in this study (Figure 2). Sugden's (1977) model reconstructed the Laurentide Ice Sheet based on the properties of existing ice sheets in Greenland and Antarctica. Boulton et al. (1985) depicted ice thickness of between about 250 and 900 m in the vicinity of the Iowa-Minnesota border (estimated from Figures 23 and 10b, respectively, Boulton et al. 1985). While the lower limit calculated by Boulton et al. (1985) falls within the limits calculated in this study, the upper limit is nearly twice as much as the calculated maximum. Boulton et al.'s (1985) minimum ice thickness was calculated allowing for deformable basal sediment in the marginal areas of the Laurentide Ice Sheet; the model used to calculate the maximum values did not. Clark et al. (1996) depicted ice thickness of about 700 m in the vicinity of the Iowa-Minnesota border (estimated from Figure 2, Clark et al. 1996), and noted that their calculations represent an upper limit for ice thickness. Clark et al.(1996) arrived

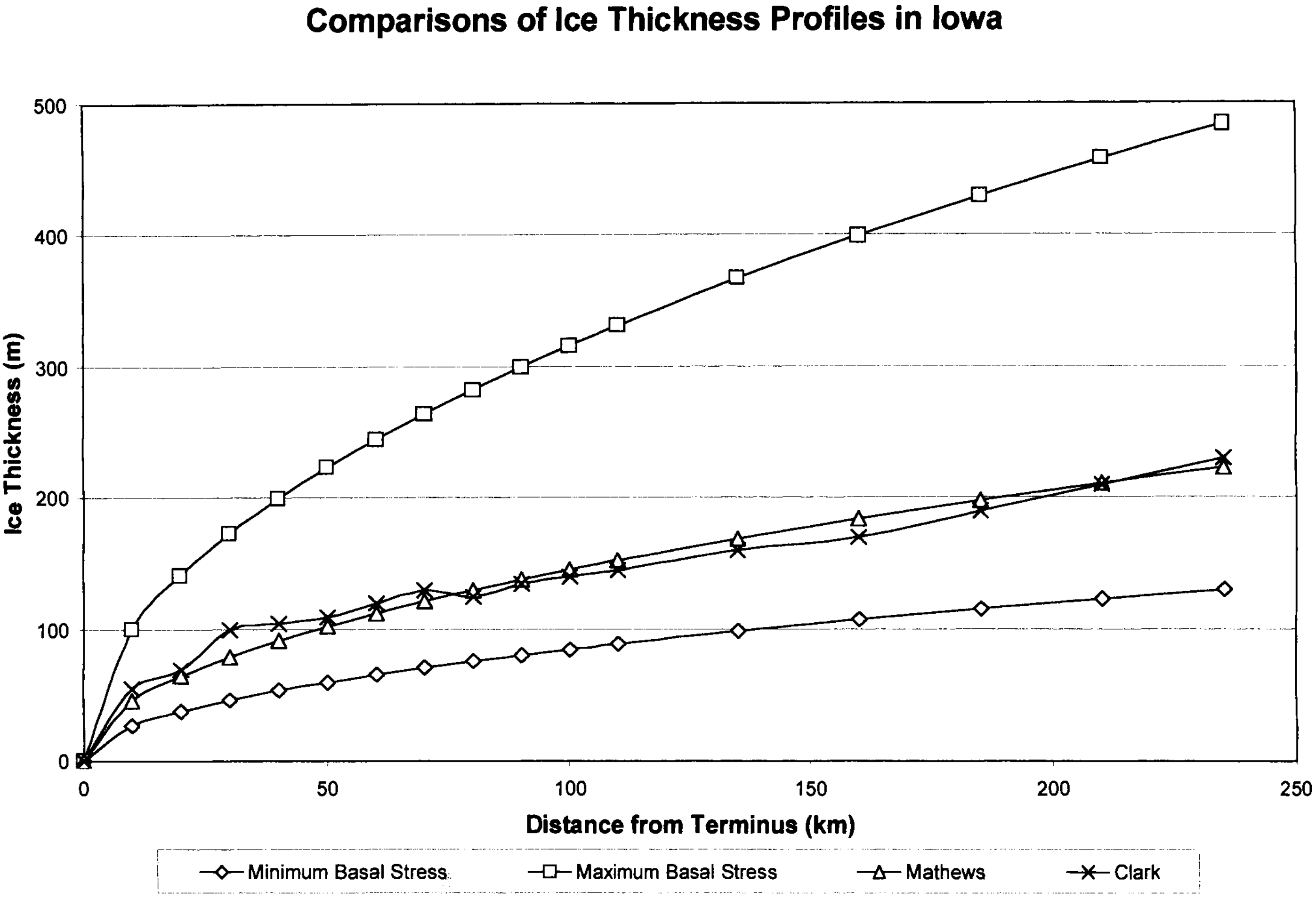

Fig. 2. Limits to ice thickness in Iowa during the Late Wisconsinan, calculated using basal shear stress values from Brevik and Reid (in press). Profiles from the studies by Mathews (1974) and Clark (1992) are compared to the minimum and maximum ice thicknesses calculated in this study.

at their ice thickness values by modeling internal deformation of the ice and allowing for deformable basal sediment.

Peltier (1994) and Hughes (1985) modeled all ice sheets in both North America and Eurasia. Peltier (1994) depicted ice thickness in the vicinity of the Iowa-Minnesota border at about 700 m (estimated from Figure 5A, Peltier 1994). Peltier's (1994) model was based on gravitational and sea level data. Hughes (1985) depicted ice thickness in the vicinity of the Iowa-Minnesota border at between 1,600 and 1,800 m (estimated from Figures 4 and 5, respectively, Hughes 1985), values that are 3 to 4 times thicker than the maximum ice thickness calculated in this study. Hughes' (1985) model was based on a basal shear stress equation introduced by Orowan (1949) and climate records from deep ocean cores.

Because of the small scale of the studies by Sugden (1977), Peltier (1994), Boulton et al. (1985), Clark et al. (1996) and Hughes (1985), no attempts were made to reconstruct profiles from the Des Moines Lobe terminus to the Iowa-Minnesota border from them. However, the profile constructed from the minimum ice thickness calculated by Boulton et al. (1985) would be similar to the profiles from Mathews (1974) and Clark (1992), and profiles constructed from Peltier's (1994) and Clark et al.'s (1996) studies would not be significantly different from the maximum ice thickness profile calculated during this study. Any profile constructed using Sugden's (1977) or Hughes' (1985) studies would show ice thickness well above the maximum values calculated in this study at all points but the glacial terminus, as would a profile constructed from Boulton et al's. (1985) maximum estimate. A graphical comparison of the various ice thickness estimates compared here is given in Figure 3.

The common link between studies that predict thin Des Moines Lobe ice is that each of these studies incorporates some measurable property or effect of the Laurentide Ice Sheet into their ice thickness model. Mathews (1974) used moraine elevations, and Clark (1992) combined moraine elevations with ice flow indicators. Peltier's (1994) reconstruction relied heavily on gravitational data from the areas that the Laurentide Ice Sheet once covered, Clark et al. (1996) coupled ice flow properties with the deformable bed that is believed to have existed beneath the margins of the Laurentide Ice Sheet, and Brevik and Reid (in press) used crustal depression due to the weight of the Des Moines Lobe ice as indicated by Lake Agassiz strandlines. This study uses the basal shear stress values for the Des Moines Lobe reported by Brevik and Reid (in press) and an equation based on the deformable bed theory to calculate ice sheet profiles in Iowa. In contrast, the studies that predict thick Des Moines Lobe Ice (i.e. Sugden 1977, Hughes 1985) are often based on models that assume a rigid substrate.

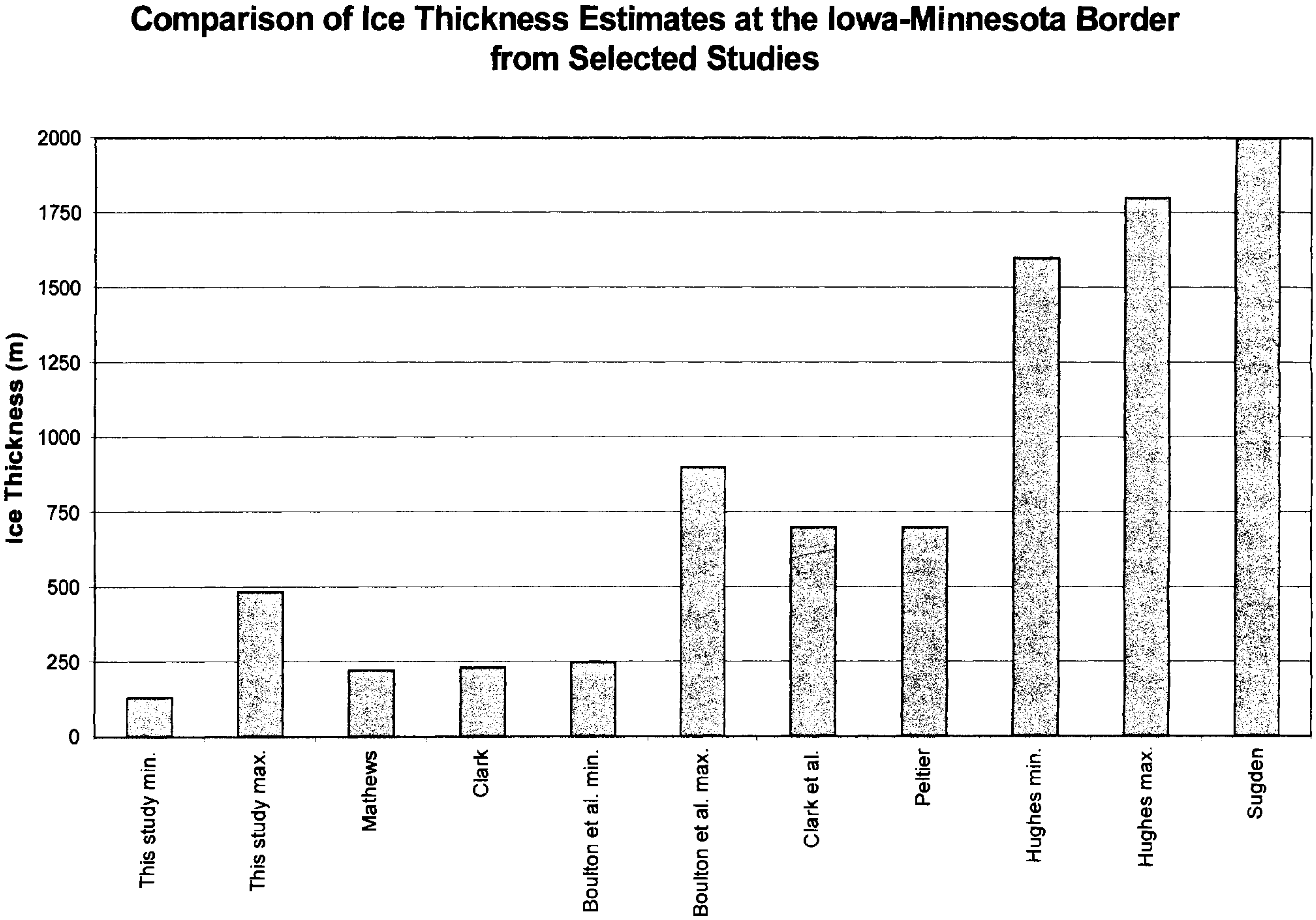

Fig. 3. Comparisons of ice thickness estimates at the Iowa-Minnesota border (point A′ from Figure 1) from several studies, including this study, Mathews (1974), Clark (1992), Boulton et al. (1985), Clark et al. (1996), Peltier (1994), Hughes (1985), and Sugden (1977). The three thickest estimates, given by Hughes (1985) and Sugden (1977) are based largely on studies of current ice sheets in Greenland and Antarctica.

CONCLUSION

Several researchers have concluded that ice in the Des Moines Lobe, which included north central Iowa, was thinner than initially believed by the geologic community. These studies (Clark et al. 1996, Peltier 1994, Clark 1992, Boulton et al. 1985, Mathews 1974) are based on a number of different approaches, as discussed earlier in this paper. Brevik and Reid (in press) calculated minimum and maximum ice thickness in eastern North Dakota based on the amount of crustal depression indicated by Lake Agassiz strandlines. The reconstruction by Brevik and Reid (in press) supports previous research that indicates the margins of the Laurentide Ice Sheet were composed of relatively thin ice. This study expends the research done by Brevik and Reid (in press) into Iowa, using a basal shear stress equation to calculate ice thickness and construct ice sheet profiles (Beget 1986). This study indicates that Des Moines Lobe ice in north central Iowa was probably between about 131 and 484 m thick. These limits are consistent with ice thickness values published for this area by a number of other researchers (Clark et al. 1996, Peltier 1994, Clark 1992, Mathews 1974, minimum ice thickness calculation by Boulton et al. 1985).

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