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GEOLOGIC CONTROLS ON THE INITIATION OF RAPID BASAL MOTION FOR WEST ANTARCTIC ICE STREAMS: A GEOPHYSICAL PERSPECTIVE INCLUDING NEW AIRBORNE RADAR SOUNDING AND LASER ALTIMETRY RESULTS

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The Ross Embayment of West Antarctica is characterized by the presence of the Siple Coast ice streams. The physical processes that enable their enhanced flow are subject to debate, but rapid basal motion (RBM) seems to be required. Basal conditions are indicative of the governing processes for overall ice stream behavior. As such, heterogenous boundary conditions implied by the analyses presented here are a crucial, but missing, component of models of the evolution of the ice stream system. We review existing geophysical data and examine new aerogeophysical results in an effort to identify geological controls on the initiation of RBM for the ice stream B and C system of the Southeastern Ross Embayment. Both seismic and aerogeophysical observations are compatible with a model of tectonic evolution for this region that implies Cretaceous rifting with a generally quiescent mid-Cenozoic punctuated by localized volcanism. This volcanism is associated with pre-established zones of crustal weakness. From the new aerogeophysical results we identify a band of transitional ice flow that separates the internally deforming interior ice and the fully developed ice stream system characterized by RBM. Four ice stream branches are clearly defined at the down-stream limit of this band. There exists a strong correspondence of this zone of RBM initiation with the transitional crust lying between the cold, thick and elevated crust of the Ellsworth/Whitmore crustal block and the warm, thin and depressed crust of the Ross Embayment. It appears that ice stream initiation relies on the availability of mid-Cenozoic sediments draped on the pre-existing rift-controlled topography of the embayment and up onto the flanks of the surrounding crustal blocks. Additionally, the gradient of regional geothermal flux across this zone cannot be ignored as potentially important. A third possible geologic control on the initiation of RBM is focused geothermal flux associated with localized volcanics both along the crustal block boundaries and within the Southeastern Ross Embayment.

INTRODUCTION

The ice streams of West Antarctica's Ross Embayment are differentiated from the inland ice of the West Antarctic ice sheet (WAIS) by their relative speed; however, the transition from slow flow to fast flow has been difficult to define. This transition is almost certainly controlled by the initiation of rapid basal motion (RBM) and the propagation kinematically of this initiation upstream into the inland ice to a point where the velocity becomes a function dominated by the driving stress [*Alley* and *Whillans*, 1991]. For the purposes of this paper we will define the onset of ice streaming to be the transition zone bounded downstream by the initiation of RBM and upstream by the limit of the kinematic response to this initiation as reflected in the driving stress. Our objective is to determine if the initiation of

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RBM is controlled by geological characteristics of the subsurface other than subglacial topography.

The foundation for the hypothesis that subglacial geology controls the initiation of RBM is based on the general observation that some combination of saturated (and possibly mobile) sediments [e.g., *Blankenship et al.*, 1986; *Engelhardt et al.*, 1990] and thin (lubricating) water layers or gaps (possibly with canals) [*Engelhardt* and *Kamb*, 1997] is necessary but perhaps not sufficient for the RBM of ice stream B in West Antarctica. There is substantial debate over the relative contributions to RBM of distributed deformation within mobile saturated sediments verses sliding over any thin lubricating water or sediment layer [*Alley*, 1989; *Engelhardt* and *Kamb*, 1998]. The end-members of this debate imply different hypotheses for geological controls on the initiation of RBM. For the end-member where RBM is caused exclusively by deformation within saturated sediments [*Boulton* and *Jones*, 1979; *Alley et al.*, 1986, 1987a, 1987b] a substantial source of easily eroded sediment is a necessary condition. In this case, the expected geological controls on initiation of RBM would range from a strong correlation either with the tectonically controlled boundary of a sedimentary basin or an erosionally controlled boundary of a much thinner but regionally extensive sedimentary drape. It is important to note that for any combination of deformation and sliding, sediment availability is a necessary but not sufficient condition because water is also required. So, for the sliding end member or for any combination of deformation and sliding, geological controls on the initiation of RBM might also include variability in regional geothermal flux caused by thinner crust or contrasting thermal histories for adjacent crustal blocks [*Stern* and *ten Brink*, 1989] to a focusing of geothermal flux by volcanic activity [*Blankenship et al.*, 1993]. In all of these scenarios, increased geothermal flux may be a sufficient condition for the initiation of RBM but it is unlikely to be necessary because the simple concentration of water by gradients in the subglacial hydrological potential [*Anandakrishnan* and *Alley*, 1997; *Hindmarsh*, 1998] could provide an adequate supply for RBM even in the absence of heterogeneous geothermal flux [*Rose*, 1979].

What these glaciological hypotheses show is that knowledge of any correlations between subglacial geological character and the initiation of RBM is essential to our understanding of the mechanics of RBM. In addition, if subglacial geology provides a necessary condition (other than the topographic framework) for the initiation of RBM in the Ross Embayment, the inclusion of this heterogeneous and largely time-invariant boundary condition would be necessary for accurate models of WAIS evolution. Interestingly, this seems to be the case for the former ice sheets of the Northern Hemisphere [*Clark* and *Walder*, 1994].

THE ROSS EMBAYMENT AS A GEOLOGICAL FRAMEWORK FOR RBM

A general understanding of the crustal evolution of the Ross Embayment (see Dalziel and Lawver, this volume) has been obtained from the outcrops surrounding the WAIS combined with subglacial topography (Figure 1) from a comprehensive program of airborne radar sounding undertaken in the 1970's [*Drewry*, 1983; see also *Rose*, 1982 and *Jankowski* and *Drewry*, 1981]. The Southeastern portion of the Ross Embayment (SERE), which is dominated by the Siple Coast ice streams, is characterized by thin extended crust with subdued topography (a few hundred meters below sea level) bounded to the north by the Marie Byrd Land crustal block (MBL) and to the south by the Transantarctic Mountains (TAM). Downstream, this thin extended crust is thought to extend beneath the Ross Ice Shelf where it continues onto the Ross Sea continental shelf. Upstream of the southernmost Siple Coast ice streams (A, B and C of Figure 1) the ice sheet is underlain by the elevated and rougher topography of the Ellsworth/Whitmore Mountains crustal block (EWB). To the north of these ice streams and adjacent to the EWB lies the deep trough of the Bentley Subglacial Trench.

Any hypothesis regarding geological controls on RBM in the SERE is critically dependent on the nature of the "rifting" event that resulted in the thin crust that forms the cradle for the Siple Coast ice streams. Although the specific cause is debated, it is well documented that a period of rifting associated with Gondwana breakup in the Cretaceous is responsible for most of the crustal thinning in the Ross Embayment [*Lawver et al.*, 1991]. It has also been hypothesized that this rifting was reactivated in the late Cenozoic [*Behrendt* and *Cooper*, 1991; *Behrendt et al.*, 1992] by interaction with an extensive mantle plume (encompassing the entirety of the SERE and MBL) resulting in large-scale volcanism and possibly flood basalts. These two histories of crustal thinning and associated volcanism have contrasting implications for geologic controls on RBM in the SERE.

Because the East Antarctic ice sheet is likely to have been present throughout much of the latter half of the Cenozoic [see *Van der Wateren* and *Hindmarsh*, 1995, for a review] and by comparison the WAIS is viewed as relatively ephemeral at least until the Pliocene [*Scherer*, 1991], it is expected that mid-Cenozoic (Oligocene and Miocene) sedimentary deposition in the SERE would be dominated by high rates of glacial marine sedimentation from East Antarctic sources (except, for brief periods of deglaciation in West Antarctica through the Pleistocene [*Scherer*, 1998]). In the case of reactivated Cenozoic rifting in the Miocene [*Behrendt et al.*, 1996], much of

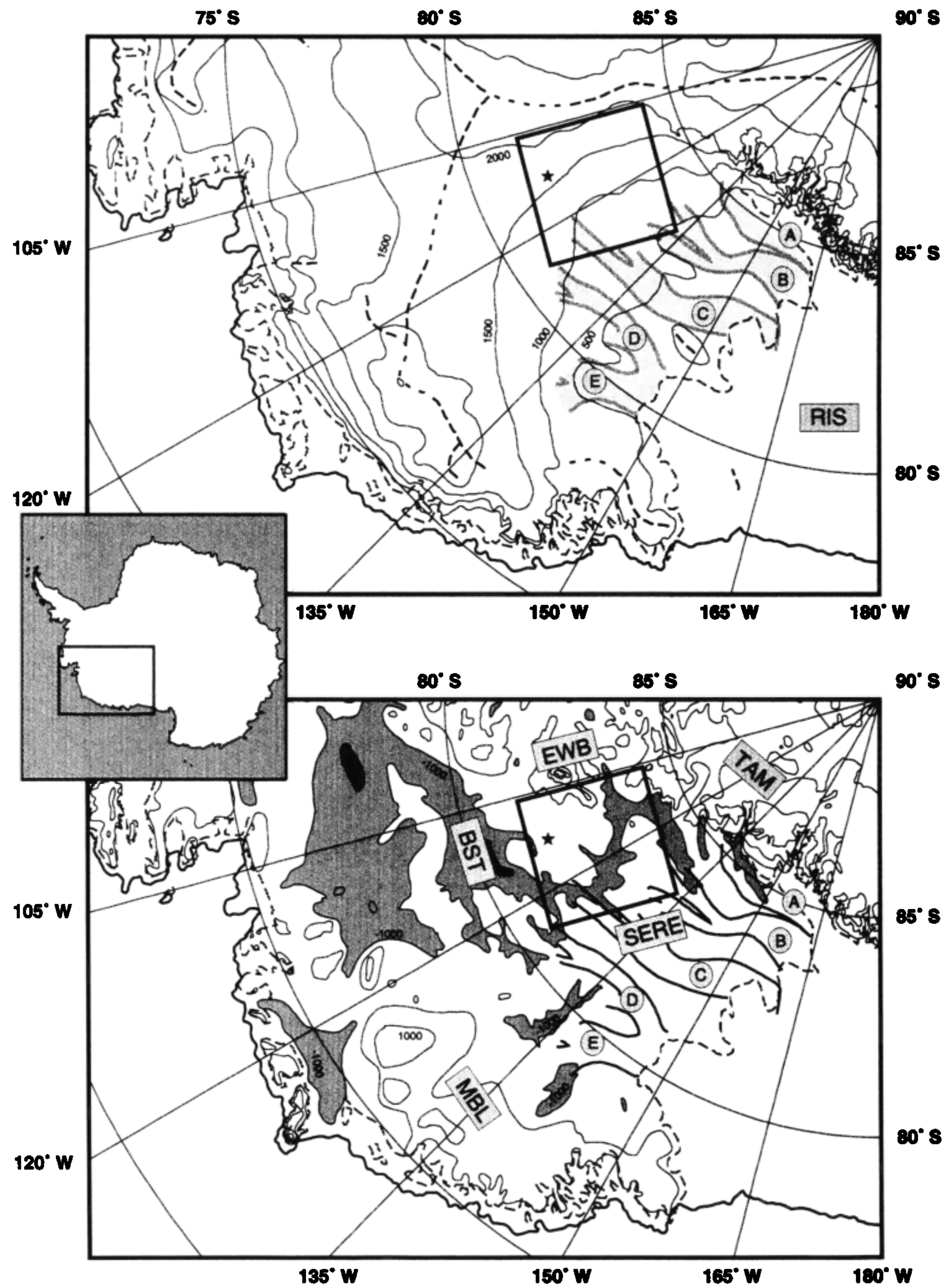

Fig. 1. Ice streams of the Ross Embayment of West Antarctica (labeled A through E) shown on the ice sheet surface (a) and subglacial topography (b) of Drewry (1983). For the surface topography the contour interval is 500 m. The subglacial topography is represented by a 1000 m contour interval with shaded topography below -1000 m a.s.l. The CASERTZ aerogeophysical survey over the Southeastern Ross Embayment (SERE) is outlined by the box overlying the catchments of ice streams B and C. EWB and BST, respectively, mark the locations of the Ellsworth/Whitmore crustal block and the Bentley Subglacial Trench; Marie Byrd Land (MBL), the Transantarctic Mountains (TAM) and the Ross Ice Shelf (RIS) are shown as well. The star indicates the location of possible active subglacial volcanism (Blankenship et al., 1993).

this mid-Cenozoic sediment would have been deposited syn-tectonically in structurally controlled sedimentary basins that may or may not be coincident with pre-existing Cretaceous grabens. For rifting limited to the Cretaceous, mid-Cenozoic marine sedimentation in the SERE would be primarily controlled by topography and therefore only subject to the indirect structural controls on this topography. In this case the mid-Cenozoic sediments would form a drape of variable thickness over the structurally controlled Cretaceous topography (and older sediments) with the greatest thickness in the topographic lows.

The expected distribution of geothermal flux would also be different for the two rift-timing scenarios in the Ross Embayment. For plume-reactivated Cenozoic rifting, the crust of the SERE would be expected to be characterized by high regional heat flow with large scale volcanism arising from zones of weakness associated with primary rift structures [*Behrendt et al.*, 1994]. For rifting limited to the Cretaceous, the regional heat flux in the SERE should remain elevated relative to the surrounding crustal blocks because of the thinned crust. In this case however, any focused geothermal flux would be associated with volcanics probably derived from local mantle sources and emplaced along zones of weakness associated with the original rifting; it has been hypothesized that these zones of weakness were reactivated in the late Cenozoic as a result of plume related uplift limited to MBL (see Dalziel and Lawver, this volume).

What we can envision are different relationships between any Cenozoic volcanics and sediments from these two rift-timing scenarios for the SERE. For the case of plume-reactivated rifting in the Cenozoic we would expect syn-tectonic sedimentation with widespread volcanic capping and further structurally controlled sedimentation. For rifting limited to the Cretaceous, we would expect a mid-Cenozoic sediment drape of variable thickness over a rift controlled topography; the deposition of this drape could have been interrupted by volcanic emplacements from localized sources following possibly reactivated zones of weakness left from the Cretaceous rifting episode. Because Cretaceous rifting is not plume related, the volume of associated Cretaceous volcanics underlying these sediments would likely be smaller than for Cenozoic plume-reactivated rifting.

The impact of these contrasting rift-timing scenarios on the initiation of RBM in the SERE is clear. The stronger structural control of mid-Cenozoic sedimentation contemporaneous with plume-reactivated rifting would provide a reasonably rigid framework for the initiation of deformation-dominated RBM. This framework would be characterized by fault-bounded sedimentary basins and extensive interlayered (or capping) volcanics. On the other hand, a tectonically quiescent mid-Cenozoic and the resulting topographically controlled drape of sediments punctuated locally by volcanics would provide fewer spatial constraints on RBM except for the lack of long-term sediment sources represented by deeper structurally controlled sedimentary basins.

For both rift-timing scenarios we expect a higher regional geothermal flux for the SERE with respect to the colder thicker crust of the EWB; however, the plume-reactivated Cenozoic rifting scenario would presumably be associated with higher and more variable heat flux in the SERE accompanying widespread volcanism. For the case of rifting limited to the Cretaceous, any focused heat sources would be associated with locally concentrated volcanics (associated with zones of crustal weakness) that are less likely to cover substantial portions of the mid-Cenozoic sedimentary drape. In either of these cases, heterogeneous heat flux could cause enhanced concentrations of basal meltwater that would be available for the initiation of RBM.

SEISMIC EVIDENCE FOR POSSIBLE GEOLOGICAL CONTROL ON RBM IN THE SERE

Specific knowledge of the geological framework for RBM in the SERE has been limited until recently and, even now, seismic evidence relevant to resolving the critical issue of rift timing is sparse but not inconsequential. During the 1980's seismic reflection surveys over ice stream B confirmed the close association of rapid basal motion and low-velocity subglacial sediments [*Blankenship et al.*, 1986; 1987; Atre and Bentley, 1994]. More extensive reflection surveys over ice stream B [*Rooney et al.*, 1987a; 1991] showed that low-velocity and very likely mid-Cenozoic sediments do exist in the topographic low beneath this ice stream and that the thickness of these low-velocity sediments was generally less than one kilometer. (Paleontological studies of subglacial sediments recovered from the seismic site on ice stream B also indicate a mid-Cenozoic age for these sediments [*Scherer*, 1991]).

Rooney et al. [1987b; 1991] used seismic refraction and reflection techniques to show that, at least at one location on ice stream B, these sediments were underlain by either older sediments with a higher-velocity or crystalline basement; they also showed that a fault in this higher-velocity unit possibly formed a lateral boundary for the lower-velocity sediments which seemed to coincide with the northern boundary of ice stream B. On the other hand, Munson and Bentley [1992] interpreted seismic refraction work on ice stream C to show that a thin O(100 m) drape of low-velocity sediments rests on a higher-velocity unit of crystalline rock or older sediments without apparent structural control. Interestingly, they also infer a kilometers thick and presumably structurally controlled low-velocity unit under the ice ridge between ice streams B and C; however, the velocity for this unit is poorly constrained.

More recent seismic refraction work near the initiation of RBM for the ice stream B/C system (ice stream C1b of Plate 1*b*) has indicated a low-velocity sedimentary unit that is coincident with RBM [*Anandakrishnan et al.*, 1998] and that covers the base of a trough which appears from aerogeophysical interpretations [*Bell et al.*, 1998] to be fault bounded. However, Anandakrishnan et al. also show evidence that a thinner drape of these low-velocity sediments (that is not coincident with RBM) is present in an adjacent shallow trough which from the aerogeophysical results appears to lack structural control.

From these sparse seismic observations it appears that low-velocity and probably mid-Cenozoic sediments are uniquely associated with RBM in the SERE. In addition, up to one km of these sediments can reside in structurally controlled topographic lows. However, the frequent occurrence of a drape of low-velocity sediments with a thickness of up to a few hundred meters indicates that sedimentation probably did not occur in concert with large-scale Cenozoic rifting; the seismic results are more consistent with mid-Cenozoic sediments draping a preexisting topography resulting from Cretaceous rifting processes with thicker deposits residing in former topographic lows.

Reliable seismic observations of crustal thicknesses are also reasonably rare in the SERE [see *Bentley*, 1973]. Clarke et al. [1997] have presented results from a carefully controlled refraction study along a 235 km profile over the boundary between SERE and the EWB crust. They observed a 30-km crustal thickness nearest the EWB thinning to the west at the SERE end of the profile. They concluded, based on the crustal thickness and mantle velocity, that there was little evidence for recent rifting; this is in agreement with the magnetotellurics results of Wannamaker et al. [1996] from the same area which are inconsistent with rifting in the latest Cenozoic. Clarke et al. [1997] presented no substantive evidence for a low-velocity layer at the base of the ice along their profile, although the detectable thickness for their experiment was about 100 m. The context for these particular results will be presented in the next section.

AEROGEOPHYSICAL EVIDENCE FOR POSSIBLE GEOLOGICAL CONTROL ON RBM IN THE SERE

Until recently, aerogeophysical studies of the SERE lacked sufficient resolution to address directly the issue of geological control on the initiation of RBM. However, these early studies did contribute significantly to our knowledge of the geological framework for RBM in the SERE. Early aeromagnetics work [*Behrendt*, 1964] showed that short wavelength magnetic anomalies consistent with subglacial volcanic units were common throughout the region and that many of the magnetic units likely rested in close proximity to the base of the ice; however, the longer wavelength components of these data also indicated substantial intervening thicknesses of non-magnetic rocks [*Behrendt* and *Wold*, 1963]. In addition, the reconnaissance radar sounding of the 1970's [*Rose*, 1979, 1982; *Jankowski* and *Drewry*, 1981; *Jankowski, et al.*, 1983] provided knowledge of the subglacial topographic framework for understanding the mosaic of crustal blocks bounding the SERE (see Dalziel and Lawver, this volume) as well as a comprehensive description of its ice stream system [*Rose*, 1979; see also *Shabtaie et al.*, 1987]. This work included a brief program of aeromagnetic surveying and reanalysis of previous aeromagnetic results which were used to define the boundary of the EWB and the SERE (near the origins of ice streams B and C) and largely verified the earlier observations of Behrendt and Wold [1963]. These investigators showed that the EWB/SERE boundary beneath the catchments of ice streams B and C is defined by magnetic crust that is transitional between the topographically smooth and low lying crust of the SERE and the non-magnetic, rough and elevated crust of the EWB. This broad region of intervening "magnetic" transitional crust also possesses an elevation intermediate to that characterizing the EWB and SERE. We will use the term Whitmore Mountains/Ross Embayment transitional crust (WRT) to describe it.

These crustal boundary definitions are important because, as mentioned above, the thinner rifted crust of the SERE is likely to be characterized by a regional geothermal flux higher than the continental average. (A single calculation of geothermal flux from an ice coring site on an interstream ice ridge in the SERE [*Alley* and *Bentley*, 1988] supports this hypothesis.) Therefore, any transitional crust between the relatively warm SERE and the colder thicker crust of the EWB could imply a transition in regional geothermal flux. Similarly, these crustal boundaries could be characterized by zones of weakness that could provide conduits for volcanics and associated focused geothermal flux.

During the early to mid 1990's a series of integrated aerogeophysical experiments was undertaken over the SERE where it meets the EWB. These experiments, collectively known as Corridor Aerogeophysics of the Southeastern Ross Transect Zone (CASERTZ), represent approximately 50,000 km of aerogeophysical surveying (at a 5.3 km grid spacing) accomplished with a uniquely configured deHavilland Twin Otter (see Appendix).

These experiments were designed specifically to address the issue of geological controls at the onset of the ice stream B/C system; they included observations of ice-sheet thickness from radar sounding and surface elevation from laser altimetry coupled to coincident observations of the gravitational and geomagnetic fields. Individual results from these experiments have been previously presented [*Blankenship et al.*, 1993; *Brozena et al.*, 1993; *Behrendt et al.*, 1993, 1994, 1995, 1996, 1997; *Sweeney et al.*, 1994, 1999; *Bell et al.*, 1998; 1999]. In Plate 1 we present a compilation including new ice surface elevations and subglacial topography for the SERE region derived from the laser altimetry and radar sounding components of these experiments (described in the attached Appendix); we then use the subglacial topography to establish detailed crustal boundaries. In Plate 2 we use the ice surface and ice thickness observations to calculate the driving stress for the ice sheet [following *Paterson*, 1994] in order to establish both downstream and upstream limits on the initiation of RBM. We also correlate these limits with subglacial topography. In Plate 3 we present the CASERTZ potential field observations with the interpreted crustal boundaries and calculated driving stress limits for the SERE region. We then interpret these results in the context of possible geologic controls on the initiation of RBM as represented by tectonic verses topographic control on mid-Cenozoic sedimentation and regional versus focused geothermal flux.

We first use the CASERTZ aerogeophysical results to define the zone that should include the initiation of RBM for the ice streams in the SERE survey region (i.e., C2, C1a, C1b and B2 of Plate 1). Assuming that the existence of active lateral margins indicates a downstream limit for the initiation of RBM [*Alley* and *Whillans*, 1991], Plate 2*a* shows clearly that this limit coincides well with the 50 kPa driving stress contour. The upper bound for the possible initiation of RBM (also shown in Plate 2*a*) is chosen somewhat conservatively as the 100 kPa driving stress contour consistent with ice flow dominated by internal deformation [e.g., *Paterson*, 1994].

Using the CASERTZ subglacial topography, it can be seen that the downstream limits of RBM initiation (Plate 2*b*) for ice streams C2, C1b, C1a and possibly B2 are correlated with topographic lows and that in most cases these lows continue downstream of this limit. However, for ice stream B2, RBM downstream of the initiation zone is correlated with generally elevated topography. In addition, examples of topographic lows exist within the survey area (e.g., the long linear valley in the northwest corner) that do not fall anywhere within the zone we have defined for the possible initiation of RBM. It is also interesting that the troughs associated with the downstream limit on RBM initiation for ice streams C2 and C1b are truncated by elevated topography within a few ten's of kilometers upstream of this limit; while both ice streams C1a and B2 are characterized by depressed topography above this limit. In summary, we can conclude from these observations only that topographic lows characterize the downstream limit on the initiation of RBM and that either elevated or depressed topography can exist either upstream or downstream of this limit. This evidence generally supports the concept that factors other than topography are important in determining the initiation of RBM for the ice streams of the SERE.

The CASERTZ subglacial topography (Plate 1*b*) also supports the earlier interpretation of the relationship between the SERE and its bounding crustal blocks. The rugged and relatively high elevations (above -250 m a.s.l.) of the EWB are clearly discernable running from northeast to southwest across the survey area with smoother topography of intermediate elevation (above -500 m a.s.l.) outlining the WRT crust; the very smooth topography of the SERE crust lies primarily below -500 m a.s.l. The CASERTZ subglacial topography also shows an indentation in the WRT crust in the south-central portion of the survey area. Our downstream limit for the initiation of RBM lies entirely within what would be topographically defined as Ross Embayment crust (Plates 1*b* and 2*b*) and the EWB crustal block consistently lies inland of our upstream limit (Plate 3a). The WRT crust is often present between the two limits that we have defined for the possible initiation of RBM (Plate 3*a*) and in all but one case, ice stream C1a, the boundary of the WRT block is largely coincident with our upstream limit for the initiation of RBM.

The Bouguer gravity calculated for the CASERTZ survey [*Bell et al.*, 1999] generally supports the crustal block interpretation derived from the subglacial topography (Plate 3*a*). EWB crust, as defined by the topography, is characterized by a Bouguer low which is consistent with thick (40 km and presumably cold) crust predicted from early gravity observations in the region [see *Bentley*, 1983]. Similarly, much of the SERE crust is characterized by a positive Bouguer anomaly consistent with the predicted thin (about 20 km and presumably warm) rifted crust observed elsewhere in the southern Ross Embayment [e.g., *ten Brink et al.*, 1998]. The WRT crust, as expected, has a negative Bouguer anomaly intermediate to that for the EWB and the SERE which meshes well with the 30 km crustal thickness determined by the seismic work of Clarke et al. [1997] which sampled almost exclusively the northern unit of WRT crust. It is very likely that the regional geothermal flux expected for the WRT crust would also lie between that for the EWB and SERE; this could represent an important change of boundary conditions for the upstream limit on initiation of RBM which seem to be correlated with WRT crustal boundaries.

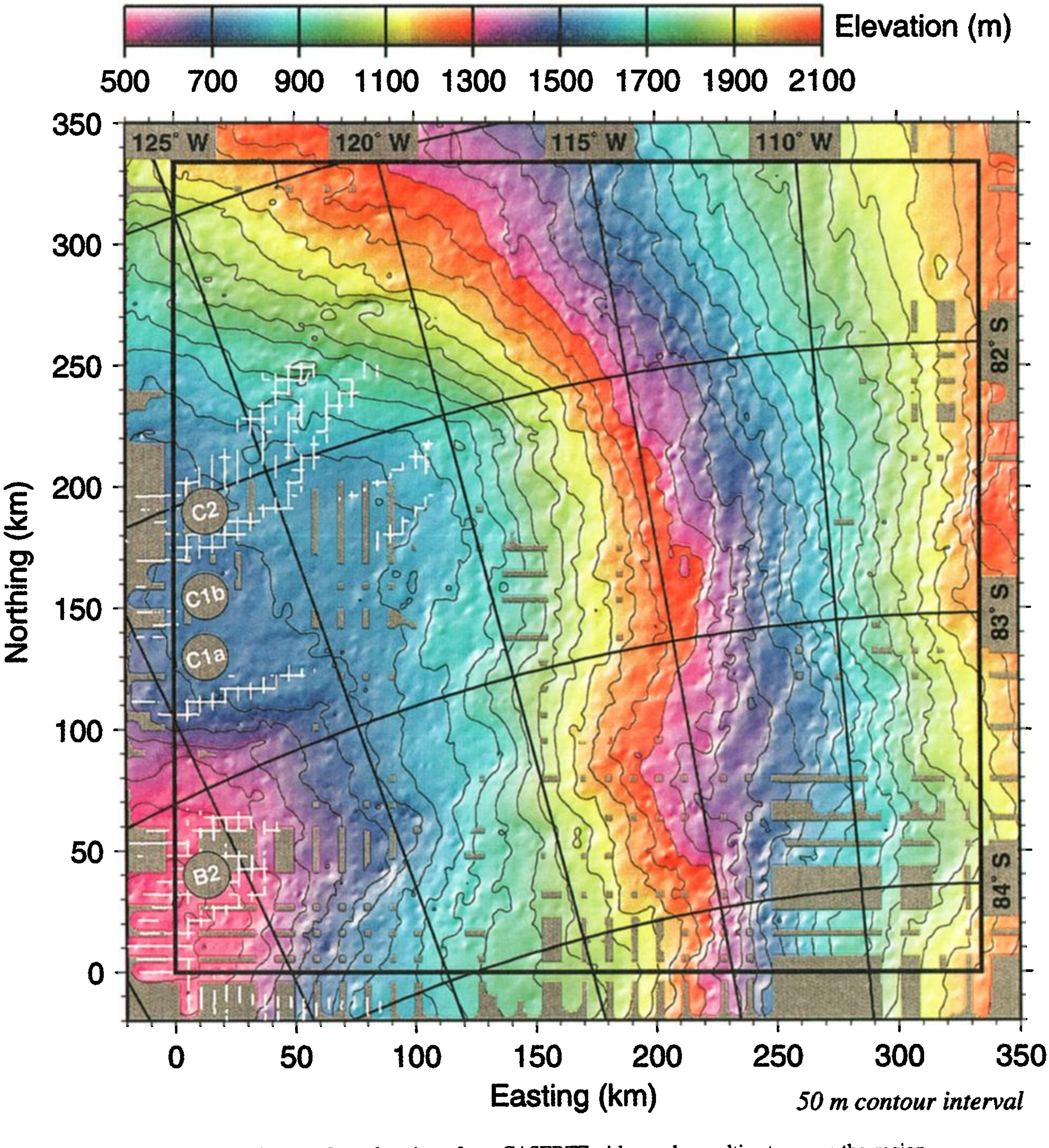

Plate 1*a*. Ice-sheet surface elevations from CASERTZ airborne laser altimetry over the region encompassing the initiation of rapid basal motion for the ice streams of the southeastern Ross Embayment. Crevassed shear margins for these ice streams as determined by airborne radar sounding are indicated by white shading along the tracklines. C2 and B2 indicate the northern limbs of ice streams C and B, respectively; C1b and C1a indicate the northern and southern tributaries of the southern limb of ice stream C. A brief description of the acquisition and interpretation of the CASERTZ laser altimetry data is presented in the attached Appendix.

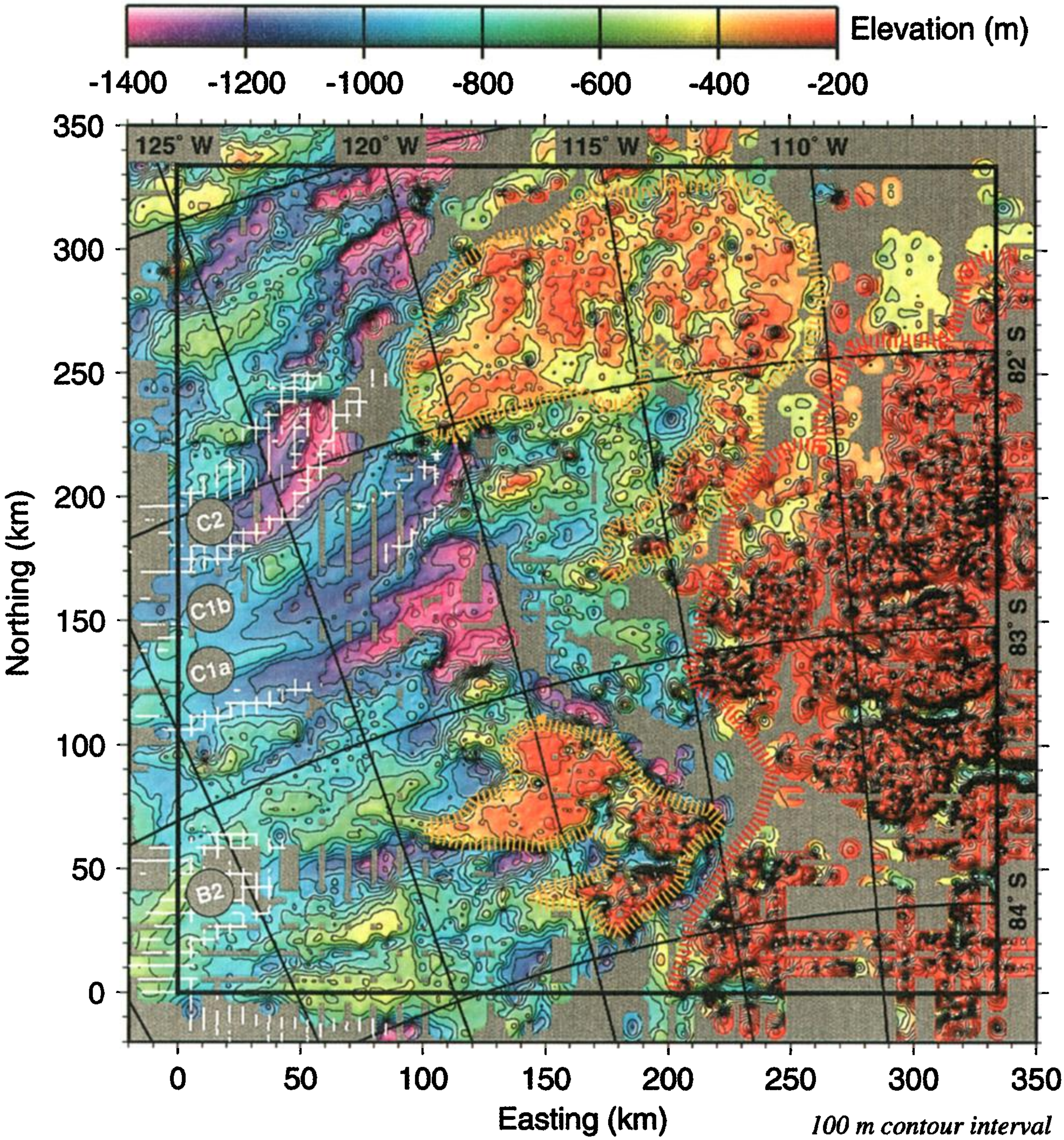

Plate 1*b*. Subglacial topography obtained by subtracting ice thickness from CASERTZ airborne radar sounding from the surface elevations of Plate 1*a*. The margins shown and naming scheme for the ice stream tributaries are the same as for Plate 1*a*. The assumed crustal boundary for the Ellsworth/Whitmore crustal block (EWB; -250m a.s.l.) is shown by the broken red line; the boundary for the Whitmore Mountains/Ross Embayment transitional crust (WRT; -500 m a.s.l.) is indicated by the broken orange line. A brief description of the acquisition and interpretation of the CASERTZ airborne radar sounding data is presented in the attached Appendix.

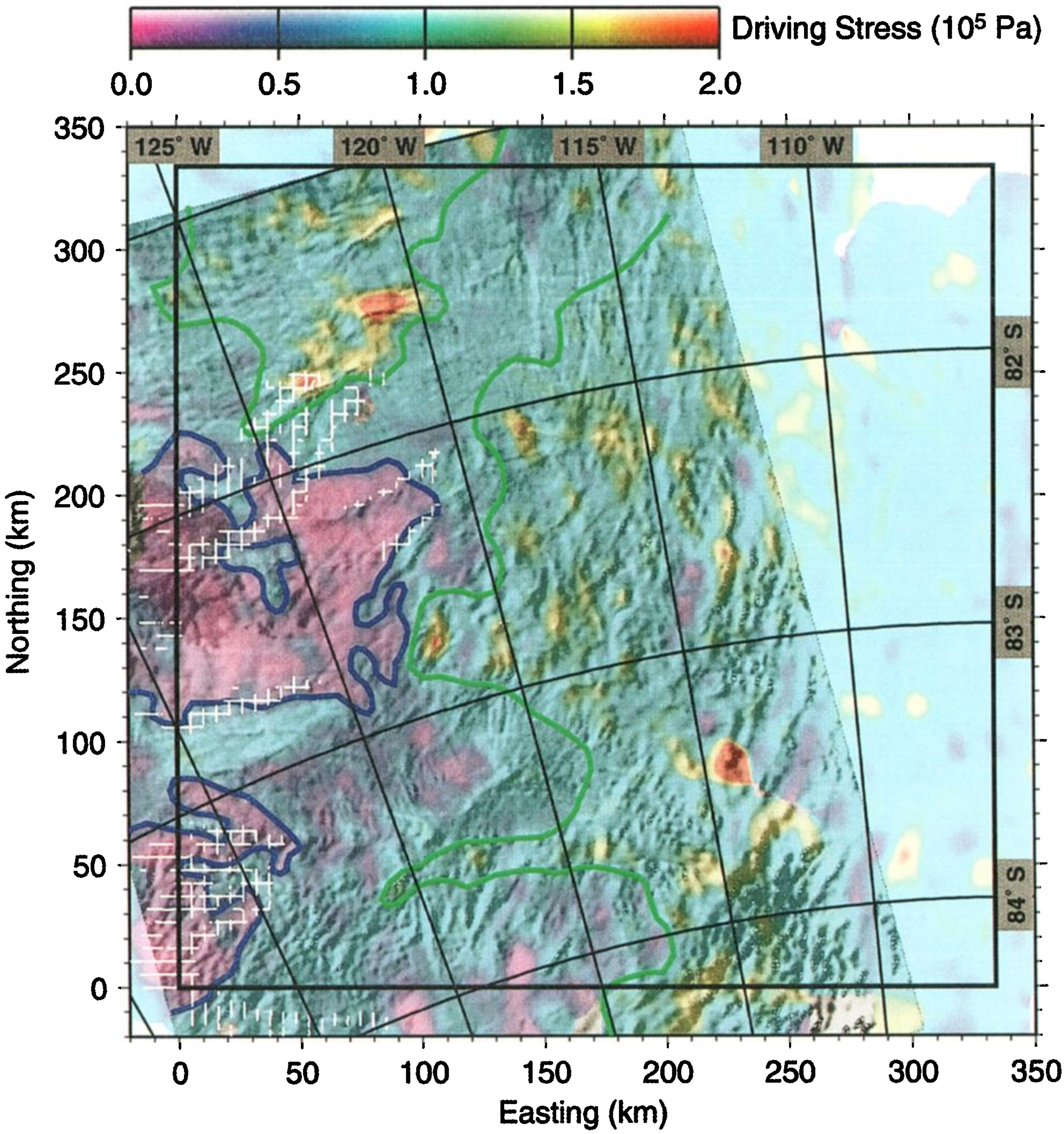

Plate 2*a*. The driving stress for the West Antarctic ice sheet calculated from Plate 1*a* and the CASERTZ ice thickness superimposed on the AVHRR image that includes this portion of the Southeastern Ross Embayment (T. Scambos, personal communication). Ice stream shear margins are as indicated in Plate 1*a*; note the agreement between these shear margins and many of the flow features apparent in the AVHRR image. Our interpretations of the 50 kPa and 100 kPa driving stress contours are indicated by the solid blue and green lines, respectively. These lines represent our estimates of the downstream (blue) and upstream (green) limits for the initiation of rapid basal motion for the ice streams of the region.

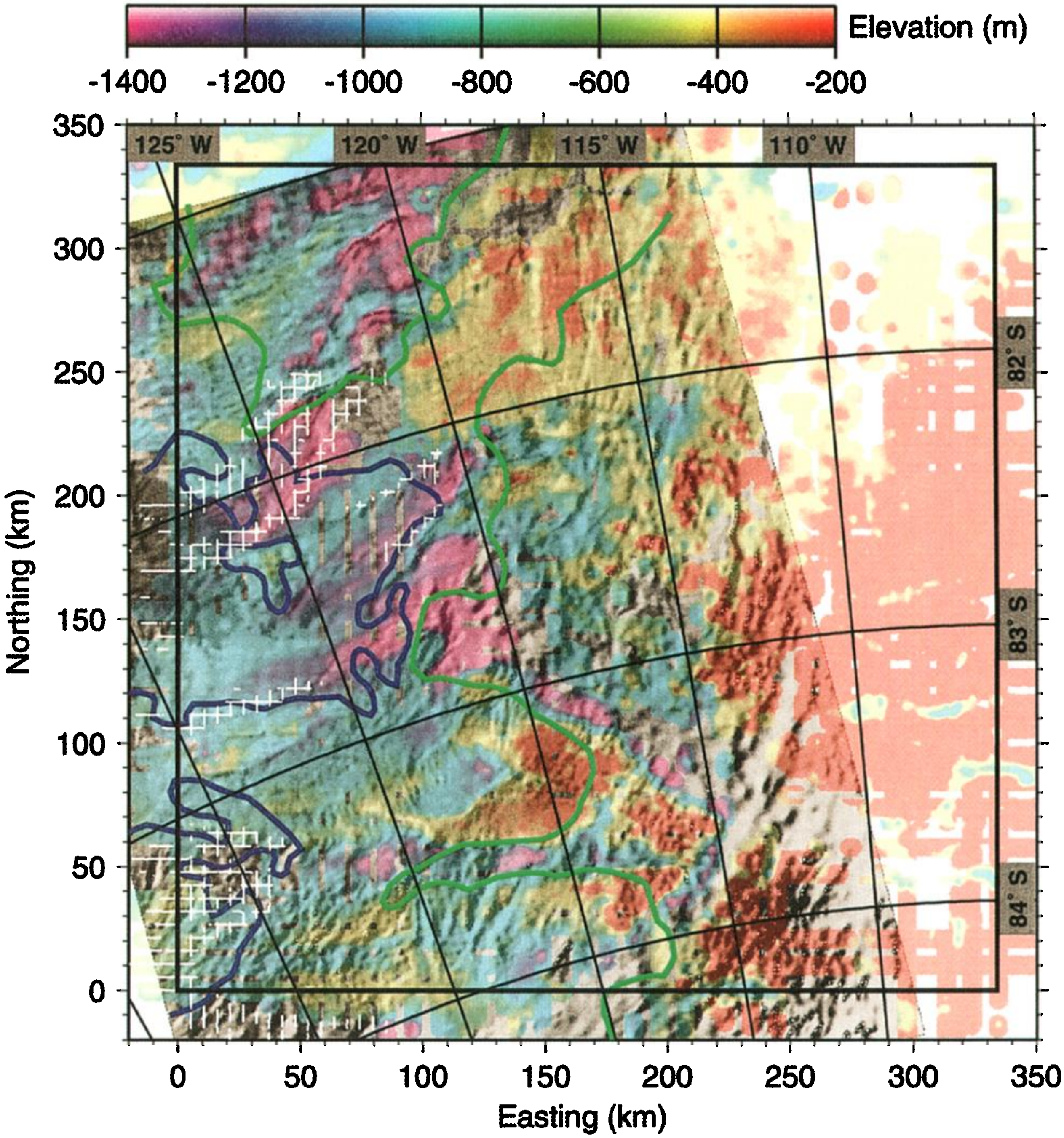

Plate 2*b*. The subglacial topography of Plate 1*b* superimposed on the AVHRR image of Plate 2*a* with our estimated downstream (blue line) and upstream (green line) limits for the initiation of rapid basal motion and active shear margins as defined for previous plates and figures. Interpretation of the relationship between subglacial topography and initiation of rapid basal motion is presented in the text.

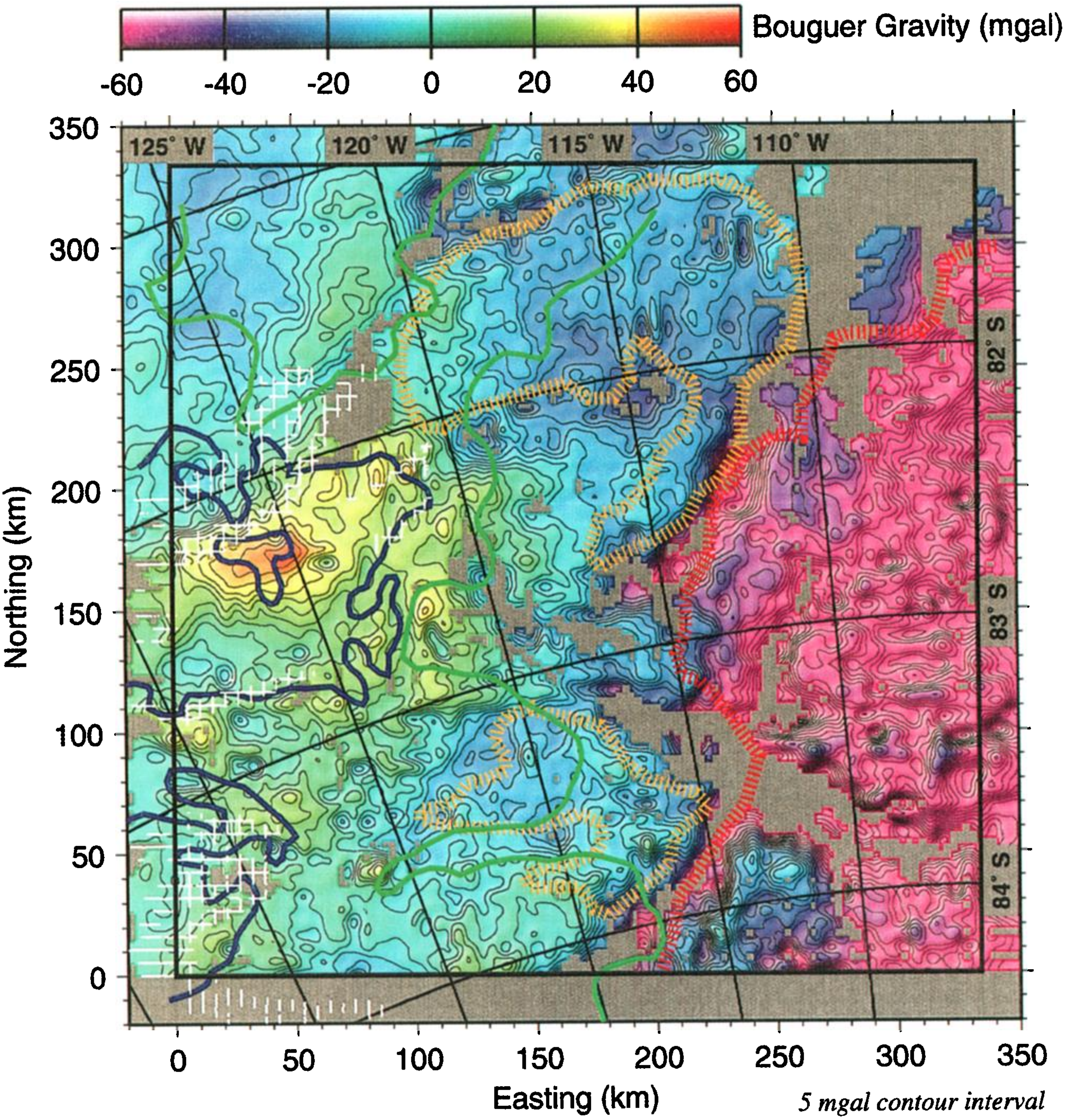

Plate 3*a*. Bouguer gravity anomalies calculated from the subglacial topography of Plate 1*b* and the CASERTZ airborne gravity observations (Bell et al., 1999).

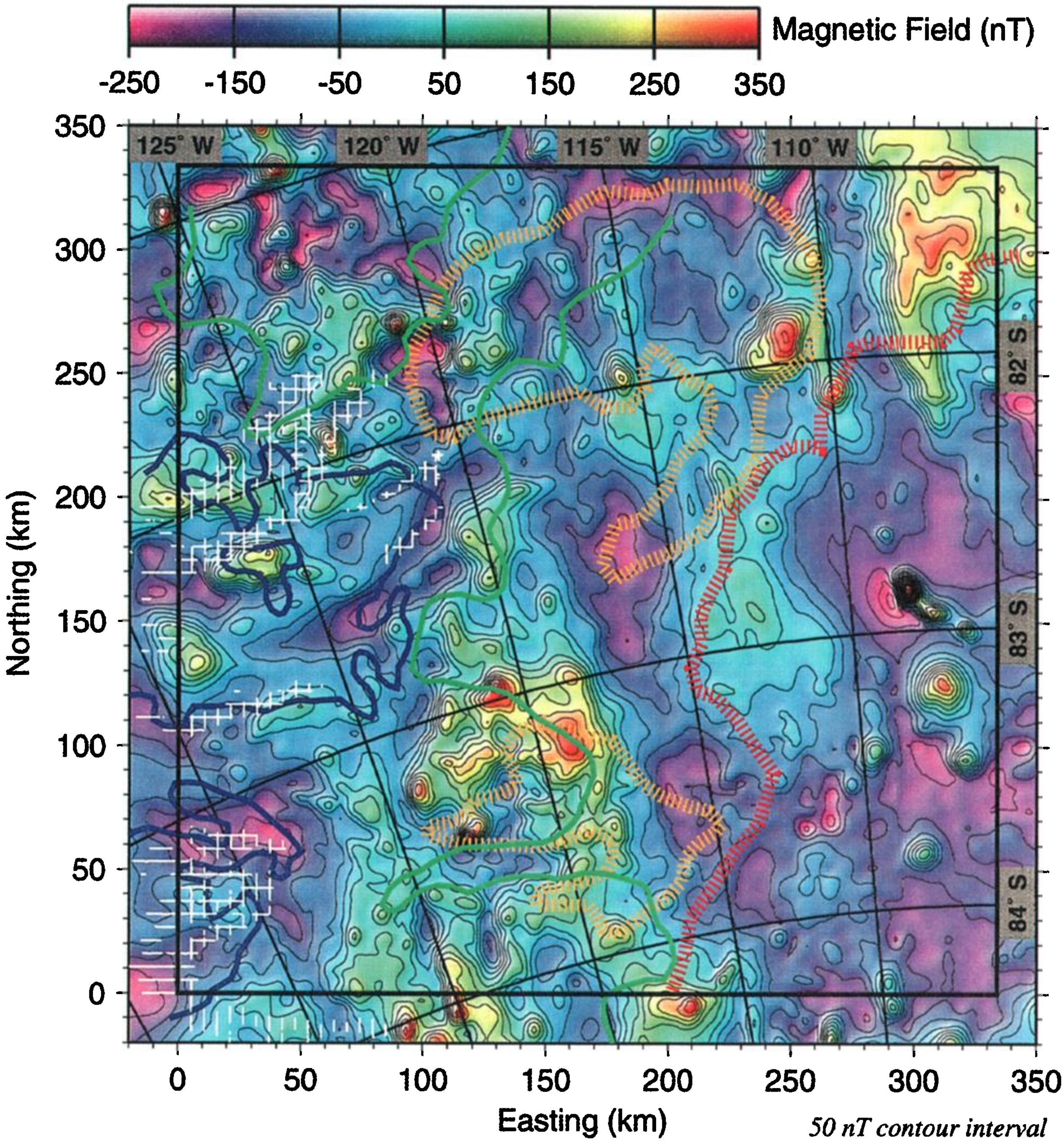

Plate 3*b*. The geomagnetic field from CASERTZ aeromagnetic surveying (Behrendt et al., 1994; Sweeney et al., 1994; 1999). For both figures, the ice stream shear margins, boundaries for the EWB and WRT crustal blocks and our limits for the initiation of rapid basal motion are as defined in Plates 1*a*, 1*b* and 2*a*, respectively.

A compilation of the CASERTZ aeromagnetic observations [*Behrendt et al.*, 1994; Sweeney et al., 1994, 1999] is presented in Plate 3*b*. In addition to the seismic work of Anandakrishnan .et al. [1998], coupled modeling of coincident lows in CASERTZ free-air gravity and magnetics observations [*Bell et al.*, 1998] showed a structurally-controlled topographic low filled with about one km of sediment within the zone of expected RBM initiation for ice stream C1b. This work supported the hypothesis of strong structural control on sediments available for the initiation of RBM but was not able to explain the lack of RBM associated with a nearby topographically controlled drape of thinner sediments. It is interesting to note that this simple relationship between free-air gravity and magnetic lows exists only for ice stream C1b and to a lesser degree for ice stream C1a; it does not exist for ice streams C2 or B2. This apparent lack of correlation could imply either a general lack of strong structural control on these sediments or interference with the simple relationship by volcanics intermingled with or capping the sediments correlated with any gravity lows. At any rate, the CASERTZ potential field data present little evidence to counter the conclusion based on seismic evidence presented above that most of the mid-Cenozoic sediments in the SERE form a drape over a structurally controlled topography resulting from rifting in the Cretaceous. Using Drewry's [1983] value of isostatic rebound for the SERE would imply a present upper limit for these mid-Cenozoic sediments of between -250 and -500 m a.s.l. which is largely coincident with the SERE/WRT crustal boundary (Plates 1*b*, 2*b* and 3*a*) and very near our upstream limit for the initiation of RBM on ice streams C1b and B2 (e.g. Plate 3*b*). Conversely, this upstream limit for ice streams C2 and C1a correlates with a bedrock elevation below -500 m a.s.l. (Plate 2*b*) making it clear that access to mid-Cenozoic sediments may be a necessary condition for the initiation of RBM but in the case of these two ice streams it may not be sufficient.

Further evaluation of the CASERTZ aeromagnetic results for the SERE (Plate 3*b*) shows that both the EWB and the northern occurrence of WRT crust are largely non-magnetic although they are punctuated by high amplitude magnetic anomalies at their boundaries (recalling that an intense low like that at 260 km north and 100 km east can represent volcanics with reversed magnetization). In addition, the far northeastern corner of the survey area shows the abutment of an anomalous region of highly magnetic crust (possibly characteristic of the Bentley Subglacial Trench) against the intersection of the EWB and WRT crustal boundaries. It is the magnetic high (centered at north 250 km and east 260 km of Plate 3*b*) near this intersection that is the proposed site of active volcanism [*Blankenship et al.*, 1993]. In addition, the northern boundary of the southern occurrence of WRT crust is dominated by a magnetic high that could represent a volcanic center for flood basalt as proposed by Behrendt et al. [1994], although no studies have yet been undertaken to establish this.

Taken in their entirety, the CASERTZ magnetic observations are generally consistent with the picture described above of localized Cenozoic volcanism concentrated at zones of weakness (i.e., along crustal boundaries) that have possibly been reactivated in the late Cenozoic by plume related uplift centered on Marie Byrd Land. Note also from these observations that in some areas the short wavelength magnetic anomalies associated with these crustal boundaries lie in the zone we have specified for the probable initiation of RBM but that frequently they do not. In particular, the best-established site for prospective active volcanism lies well above our upper limit and seems to play no role in the initiation of RBM. The conclusion from this correlation is that the simple occurrence of focused geothermal flux associated with localized volcanism is not a sufficient condition for the initiation of RBM on the crustal blocks bounding the SERE.

Within the SERE proper, the CASERTZ aeromagnetic data (Plate 3*b*) indicate numerous very localized magnetic highs superimposed on a background of moderately magnetic crust. For ice stream C2 these short wavelength anomalies correlate closely with our zone of expected RBM initiation. In addition, the upper limit for RBM initiation on ice stream C1a correlates with the edge of one of the more extensive moderate amplitude magnetic units of the SERE crust. For both of these cases the limits on the zone of expected RBM initiation lie in part quite close together (where they are characterized by variations in subglacial topography) although this relationship could result from a kinematic response to the recent shut down of ice stream C. For ice streams C1b and B2 this correlation between narrowly separated limits for RBM initiation and magnetic units does not hold. It should also be noted that the moderate magnetic high along the ice stream C1/C2 boundary correlates with the highest Bouguer gravity anomaly shown in Plate 3*a*. The mass excess required for such a dramatic high could result from a shallow mantle which could be associated with focused geothermal flux.

In summary, the CASERTZ aeromagnetic observations are generally consistent with the expected geological framework for the SERE as represented by a "marble cake" of mid-Cenozoic sediments punctuated by localized volcanics. These observations also indicate that focused geothermal flux associated with short wavelength magnetic anomalies could play a role in the initiation of RBM when these anomalies occur at an elevation that is consistent with the presence of mid-Cenozoic sediments (i.e., for ice streams C2 and C1a). However, it is also possible that the locally elevated topography associated with these anomalies could represent volcanics capping (and therefore isolating) the mid-Cenozoic sediments necessary for the initiation of RBM.

CONCLUSIONS

From the evidence reviewed and presented here, it seems that the most likely geological control on the initiation of rapid basal motion (RBM) for the ice streams of the Southeastern Ross Embayment of West Antarctica is the availability of the mid-Cenozoic sediments deposited on the pre-existing rift controlled topography of the embayment and up onto the flanks of the surrounding crustal blocks. There is little geophysical evidence for the rigid structural controls on these sediments that would result from deposition that was syn-tectonic with reactivated rifting in the late Cenozoic. The CASERTZ aerogeophysical results indicate that in two cases, ice streams C1b and B2, the existence of sediments may be both necessary and sufficient for the initiation of RBM; for ice streams C2 and C1a these data indicate that sediment availability is probably a necessary but not sufficient condition for RBM initiation. A conclusive correlation of RBM with this drape of mid-Cenozoic sediments is probably not possible with aerogeophysical techniques [see *Bentley*, 1998] because the sediments could possibly be quite thin (O(100 m)); however, a conclusive verification should be straightforward with high resolution seismic reflection [e.g., *Rooney*, 1987b] or possibly refraction [e.g. *Anandakrishnan et al.*, 1998] techniques.

An additional known geological control based on the evidence reviewed above is certainly the gradient in geothermal flux from the cold thick crust characterizing the Whitmore Mountains (EWB) across the intermediate thickness of the transitional crust (WRT) to the thinner and warmer crust of the Southeastern Ross Embayment (SERE). Estimated values for this regional geothermal flux would range from near continental average for the EWB to the measured value of about twice continental average for SERE crust [*Alley* and *Bentley*, 1988] with the flux for the WRT crust expected to lie between these two end members. The aerogeophysical results presented here show that our observed zone of probable RBM initiation for ice streams C2, C1b, C1a and B2 lies entirely over crust with an expected regional geothermal flux that is probably higher than the continental average.

A final possible geological control on the initiation of RBM in the SERE is focused geothermal flux associated with localized volcanics (or alternatively a passive volcanic capping of the mid-Cenozoic sediments). The aerogeophysical evidence presented here is entirely consistent with the existence of these volcanics, particularly along the boundaries of the WRT crust as well as throughout the SERE. The concentration of these volcanics at crustal boundaries is thought to result from their migration along zones of weakness that were reactivated by the plume-related uplift of Marie Byrd Land in the late Cenozoic (see Dalziel and Lawver, this volume). This evidence for localized volcanics and possible focused geothermal flux is in particular associated with an anomalous narrowing of the zone we expect for the initiation of RBM on ice streams C2 and C1a although the kinematic response to ice stream C's shut down may play a role. Newly developed airborne radar sounding methods for discriminating water patches on subglacial rocks and sediments beneath ice streams [*Peters et al.*, submitted] may be sufficient for investigating the relationship between focused geothermal flux and the initiation of RBM for these ice streams.

APPENDIX

Acquisition and interpretation of CASERTZ airborne radar sounding and laser altimetry observations over the Southeastern Ross Embayment.

The CASERTZ surveys over the Southeastern Ross Embayment were accomplished with 116 flights in three seasons using a uniquely configured deHavilland Twin Otter aircraft (43 and 53 flights from the CASERTZ field camp in the 1991/92 and 1992/93 field seasons, respectively, combined with 20 flights from Byrd Surface Camp in the 1995/96 austral summer.) In general, these flights were approximately four hours in duration with a survey elevation of 350 to 1000 m above the ice surface and a survey air speed of 120 to 130 knots. The technical aspects of the airborne radar sounding and laser altimetry instrumentation and the processing techniques applied to the acquired data are detailed below.

The airborne radar sounding was accomplished with a radar constructed by the Technical University of Denmark (Skou and Sondergaard, 1976) and modified for digital data acquisition initially using a data acquisition system designed and constructed by the USGS (Wright et al., 1989) which was ultimately upgraded with a system designed and constructed by the University of Texas, Institute for Geophysics. In general, this radar transmitted a 250 ns pulse at 60 Mhz with a peak power of about 8 kW at a repetition rate of 12.5 kHz. The aircraft has been modified to support "flat-plate" dipole antennas (Skou and Teilgaard, 1978) suspended 1.25 m (i.e., approximately 1/4 wavelength) beneath each wing; a signal splitter/combiner allowed both of these antennas to transmit and receive simultaneously. After the received signals have been logarithmically detected, they were digitized at a sample rate of either 20 or 40 ns; 2048 subsequent transmissions were added to improve the signal-to-noise ratio. In the early surveys, the 2048 transmissions could be digitized and integrated about twice per second (i.e., every 30 m along track); in the later surveys using the upgraded system this rate was increased to approximately five times per second (i.e., every 12 m along track).

Data interpretation consisted of the display of differentiated radar-grams followed by an "interpretation" phase consisting of interactively bounding the transmitted pulse, surface return and bedrock return. The application of an auto tracker to these bounded returns identified the times of arrival by locating the maximum of the second derivative of the signal amplitude and extrapolating it to locate the end of the quiescent signal just before the return. This process has proved to be stable with a precision of better than a sample interval. To guarantee consistency across a survey region, each interpretation was verified by a second interpreter and line-to-line comparisons were made at survey crossover points as a final check of consistency. The radar wave velocity in ice was taken to be 168.4 m/μs and no firn correction was applied. The r.m.s. deviation of ice thickness at the crossover points varies with the ruggedness of the topography from +/- 82 m for the mountainous EWM block to +/- 11 m for the smooth topography of the SERE.

Laser altimetry was utilized to establish the best absolute surface morphology for the CASERTZ aerogeophysics experiments. The laser altimeter on the Twin Otter was a 1000W peak-power infrared unit (YAG) manufactured by Azimuth Corp. This unit was capable of 1000 pulses per second; in our configuration 64 of these pulses were integrated eight times per second for a range determination approximately every eight meters. In the absence of intervening clouds, range precisions of better than 0.1 m were readily achievable at ranges of up to 1500 m. These laser ranges were corrected for aircraft attitude as determined by an Inertial Navigation System (Litton LTN-92) and projected to a spot on the ice sheet surface using the absolute position of the aircraft.

Aircraft positions were established by solving kinematic differential carrier-phase observations of the constellation of GPS satellites visible at the aircraft and at the main base of operations (Brozena et al., 1993; Bell et al., 1999). Both Ashtech Z-12 and TurboRogue GPS receivers were used at various times (and often simultaneously) to make these observations. After adjusting for linear drift along a track line, the r.m.s. deviation of one half the observational discrepancy in laser-determined surface elevations at the crossover points was calculated for each survey; these range from +/-37 cm for the earliest survey, which was undertaken before the GPS constellation was complete, to +/-9 cm for the later surveys after the constellation was complete.

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