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# ON THE USE OF STATIC GPS MEASUREMENTS TO RECORD THE TIDAL RESPONSE OF A SMALL ANTARCTIC ICE SHELF (HELLS GATE ICE SHELF, VICTORIA LAND)

**ABSTRACT:** BONDESAN A., CAPRA A., GUBELLINI A. & TISON J.L., *On the use of static GPS measurements to record the tidal response of a small antarctic ice shelf (Hells Gate Ice Shelf, Victoria Land)* (IT ISSN 0391-9838, 1994).

Recent developments of GPS (Global Positioning System) technology provide a new powerful tool to study ice shelf-ocean dynamical interactions. Here we present results from feasibility tests on the use of static GPS measurements to locate grounding zones and study their impact on the ice shelf mechanical response. The Hells Gate Ice Shelf has been chosen as a study case owing to its vicinity from Terra Nova Bay Station and to the peculiar problems it raises to glaciologists and geophysicists.

Technical and analytical problems are discussed and 5 short time lapse records, in various places at the ice shelf surface, are interpreted. Most of the survey stations appear to react fully hydrostatically to the tidal forcing, even during a secondary maximum of only a few centimeters amplitude. The most upstream station 4, located in a strait between Vegetation Island and the Northern Foothills, shows departure from hydrostatic equilibrium in accordance with a scheme of bedrock valley sides effects. The GPS curve recorded suggests that the ice shelf might not always behave elastically in grounding zones as also testified by periods of intense microseismic activity into the ice shelf during part of the day.

KEY WORDS: Global Positioning System, Ice shelf dynamics, Tidal forcing, Grounding zones.

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**RIASSUNTO:** BONDESAN A., CAPRA A., GUBELLINI A. & TISON J.L., *Uso del GPS in modalità statica per registrare l'oscillazione di marea di una piccola piattaforma antartica di ghiaccio galleggiante (Hells Gate Ice Shelf, Terra Vittoria)* (IT ISSN 0391-9838, 1994).

Il recente sviluppo della tecnologia GPS (*Global Positioning System*) offre un nuovo potente strumento per studiare le interazioni dinamiche tra piattaforme di ghiaccio galleggiante e oceano. Qui vengono presentati i risultati dei test di fattibilità finalizzati all'uso delle misure GPS in modalità statica per localizzare le zone di ancoraggio al fondo (*grounding zones*) e studiare il loro impatto sulla risposta meccanica delle piattaforme di ghiaccio galleggiante. La piattaforma di Hells Gate è stata scelta come area campione a causa della vicinanza alla Stazione Baia Terra Nova e alla particolare problematica di interesse glaciologico e geofisico.

Sono discussi i problemi tecnici e vengono interpretate 5 registrazioni a breve intervallo, effettuate in vari punti della superficie della piattaforma. La maggior parte delle stazioni di misura sembrano reagire idrostaticamente alle sollecitazioni di marea, perfino durante un massimo secondario di pochi centimetri di ampiezza. La stazione 4, localizzata più a monte di tutte, tra Vegetation Island e le Northern Foothills, mostra un allontanamento dalle condizioni di equilibrio forse per l'effetto generato dai versanti vallivi rocciosi. La curva GPS registrata suggerisce che la piattaforma potrebbe non sempre comportarsi elasticamente nelle *grounding zones*, come anche testimoniato dai periodi di intensa attività microsismica (*icequakes*) durante parte del giorno nell'area della stazione 4.

TERMINI CHIAVE: Global Positioning System, Dinamica delle piattaforme di ghiaccio galleggiante, Sollecitazioni di marea, Zone di ancoraggio al fondo.

## INTRODUCTION

Glaciological studies of the last decades have now well established the fundamental role played by ice-shelves in controlling ice-sheet mass balance. Boundary conditions at grounding lines (or pinning points), where the ice gets afloat (or regrounded), is still a critical step in simulating ice sheet sensitivity to climatic changes. Modelling needs testing against field evidences and therefore numerous attempts where made to localize grounding lines and to study their impact on ice shelf dynamics using various techniques.

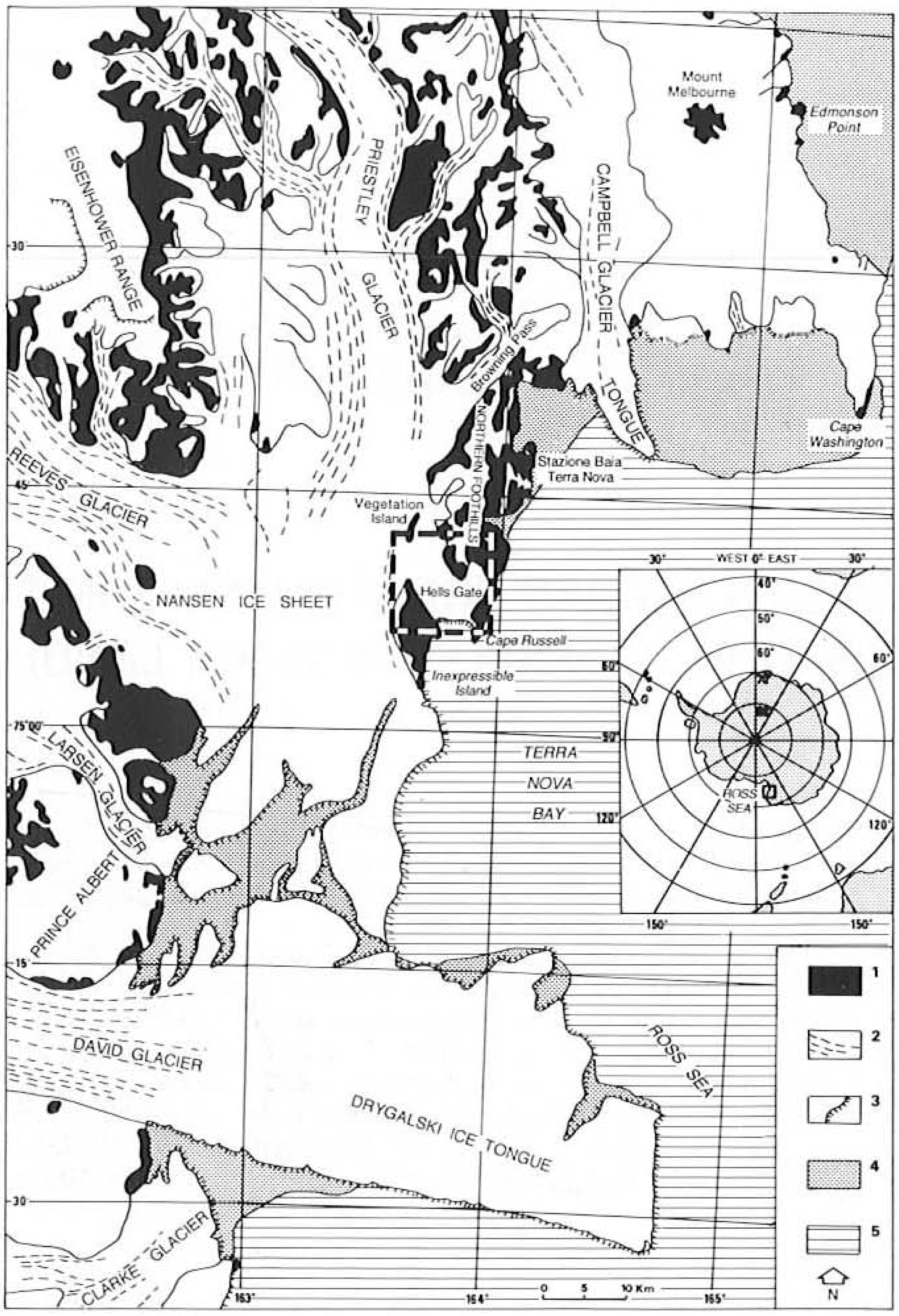


FIG. 1 - Index map of the Terra Nova Bay area (after OROMBELLI, 1986, modified). Legend: 1) Ice-free area, 2) Glacier, 3) Ice shelf and ice tongue, 4) Sea ice (Dec. 1963), 5) Sea.

Initially, before the recent development of GPS applications, the lack of any height reference on the ice shelf surface has required the use of unconventional techniques to detect the ice shelf response to tidal forcing (PEDLEY & *alii*, 1986). Gravity meters were most commonly used (after THIEL & *alii*, 1960) but also records of vertical movements of floating fast ice along the ice shelf (BISHOP & WALTON, 1977), tilt measurements of tidal flexure near grounding lines (STEFFENSON & *alii*, 1979), and pressure measurements on the sea floor (POTTER & *alii*, 1985; PEDLEY & *alii*, 1986) providing power spectrum records of tidal heights. These latter data have shown strong nonlinear response to tidal forcing on the George VI Ice Shelf (Antarctic Peninsula) that were tentatively associated to an anelastic component in the deformation of the ice near the grounding line (PEDLEY & *alii*, 1986). Most recently, JACOBEL & *alii* (1994) tested the use of Landsat thematic mapper images to infer grounding line position against an array of field measurements, namely radar profiling, velocity measurements and tilt studies of ice flexure. Their results point to the need of using several techniques in conjunction, to compensate weaknesses inherent to each individual type of measurement. Recently, repeated kinematic GPS measurements were used by VAUGHAN (1994) to locate the position of the grounding line under the Rutford Ice Stream and to analyze the mechanical response of the ice shelf to tidal forcing.

This work presents preliminary results from feasibility tests on the use of static GPS measurements to locate grounding zones under the Hells Gate Ice Shelf, a small antarctic ice shelf located in Terra Nova Bay, Victoria Land.

## THE HELLS GATE ICE SHELF

The Hells Gate Ice Shelf is located in Terra Nova Bay (Ross Sea), to the South of the Italian Antarctic Station, along the coastal belt of Transantarctic Mountains (lat. 74° 50' S, long. 163° 50' E, fig. 1). It can be considered as part of the Nansen Ice Sheet, from which it is separated along its western margin by the outcropping relief of Vegetation Island and Inexpressible Island. It extends from North to South for 16.6 km with a maximum width of 9.8 km, to the South of Cape Confusion, and its total area is more than 70 km². It is fed by the ice flow from Browning Glacier, by some small glaciers outflowing from the Northern Foothills and, partially, by the Priestley Glacier. The Hells Gate Ice Shelf is surrounded by the Northern Foothills to the East, Vegetation Island and Nansen Ice Sheet to the North, Inexpressible Island to the West and the Ross Sea to the South (Evans Cove).

Owing to its peculiarities this ice shelf has been extensively studied by glaciologists and geophysicists during the last Italian antarctic expeditions, but still its glacial morphology and dynamics raise many unsolved questions.

The ice shelf surface is conventionnally divided into three sectors, separated to the East by a twin-crested morainic ridge and to the West by two alignments of ice-cored debris cones made of massive clast-supported diamict, locally showing a sandy matrix (supraglacial till). The supraglacial morainic deposits contain a great amount of marine subfossil specimens (Serpulids, Cirripedia and various shells) thought to have been incorporated into the marine ice accreting at the ice shelf bottom, close to the grounding line (BARONI, 1990). Other complex moraines outcrop near Cape Confusion and a composite lateral moraine develops to the East of Vegetation Island.

This ice shelf is also characterized by a strong uprise of its flow lines towards the surface, due to intense surficial ablation by the katabatic winds descending from the Antarctic Plateau and blowing with great intensity and frequency across the ice shelf (hence its name, given in 1912 by the «Northern Party» of the Scott Expedition).

Hells Gate Ice Shelf was described for the first time by PRIESTLEY (1923) in its study of Robertson Bay and Terra Nova Bay and it was reproduced very precisely in a

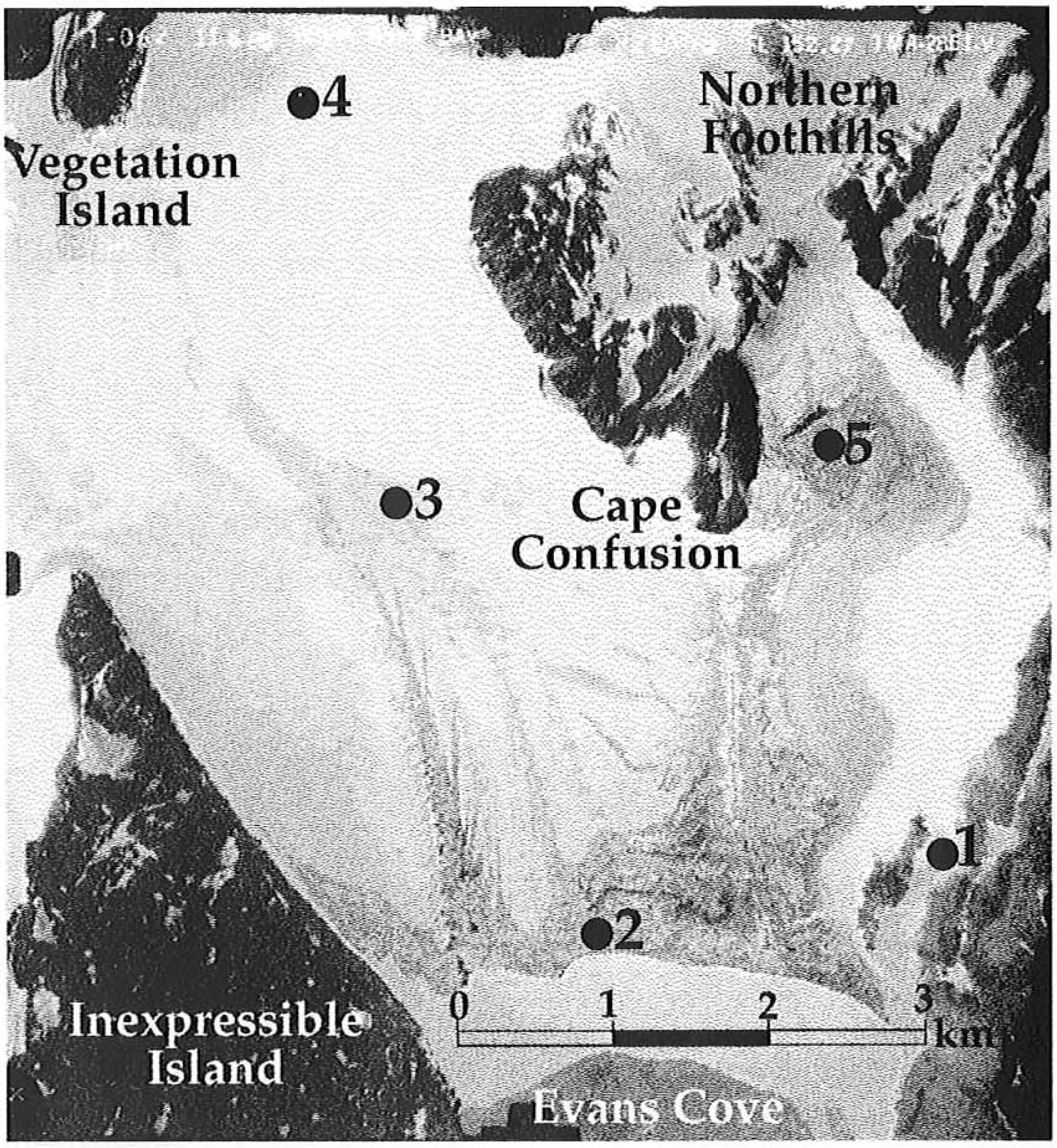


FIG. 2 - Main features of the Hells Gate Ice Shelf and survey stations location (after BONDESAN & *alii*, 1994a, b). Aerial photograph TMA-2851-V of 11-06-1985.

1:250.000 map. Later on, CAMPBELL & CLARIDGE (1975) focused on the study of the debris cones emerging between the western and central sector, and TISON & *alii* (1994b) recently proposed a dynamical model explaining the genesis of this morainic complex.

Paleoglaciological reconstruction from BARONI & OROMBELLI (1991) showed an advance of the Hells Gate Ice Shelf following a glacio-eustatic uprise of the coastal margin in the area.

Several studies also dealt with evaluation of the surficial velocity of Hells Gate Ice Shelf, based either on $^{14}C$ geochronological dating of subfossils remnants or on aerial photographs and satellite images studies (see for example, BARONI, 1990; BARONI & *alii*, 1991a, BARONI & *alii*, 1991c; FREZZOTTI, 1993). Both techniques provided similar values of about 3.3 $my^{-1}$ for the eastern moraine. On the western dirt cones alignments, however, a slight discrepancy exists between the $^{14}C$ derived velocities (10.4 to 17.4 $my^{-1}$ for shells incorporation around the southern part of Vegetation Island) and the photointerpretation (8.8 to 11.9 $my^{-1}$).

Stable isotopes measurements ($\delta^{18}O$) of ice samples from the ice shelf (BARONI & *alii*, 1991b) revealed outcropping marine ice (ice resulting from the freezing of sea water accreting at the base of the ice shelf) in its frontal zone, thereby indicating basal freezing under the ice shelf. Co-isotopic (both in $\delta D$ and $\delta^{18}O$), chemical and crystallographic analyses shed more light on the processes involved in the formation of this marine ice (SOUCHEZ & *alii*, 1991; RONVEAUX, 1992; TISON & *alii*, 1993, LORRAIN & *alii*, 1994). These studies suggested contrasted depositional environments for the different types of marine ice observed, related to the morphology of the submerged portion of the ice shelf and to the ocean circulation in front and below the ice shelf (TISON & *alii*; 1994a). Topographical measurements performed on the debris cones (BARONI, 1990) also allowed to estimate the accumulation rates due to basal freezing (5-25 $cmy^{-1}$) and the surface ablation rates (16.5 to 36.5 $cmy^{-1}$), supposing hydrostatic equilibrium.

Finally, geophysical investigations (gravimetry surveys, geoelectrical measurements, active and passive seismic and radar measurements) are about to solve the complex problem of discriminating between continental ice/ marine ice/ ocean/ bedrock interfaces returns (CANEVA & *alii*, 1994a to c; LOZEJ & *alii*, 1994).

For the purpose of the experiments related to the present work, a small network of 5 GPS survey stations was settled to record the response of the ice shelf to tidal forcing. The stations were selected as follows (fig. 2):

— station 1: designed to be the altimetric reference point it was placed on a rocky outcrop near Cape Russell;

— station 2 to 4: positioned on a longitudinal transect from the ice shelf front to the strait between Vegetation Island and the Northern Foothills; these three stations were intended to record the transition from the freely floating part to the grounded part of the ice shelf;

— station 5: was chosen to detect any tidal influence in this highly sheltered zone, to the East of Cape Confusion.

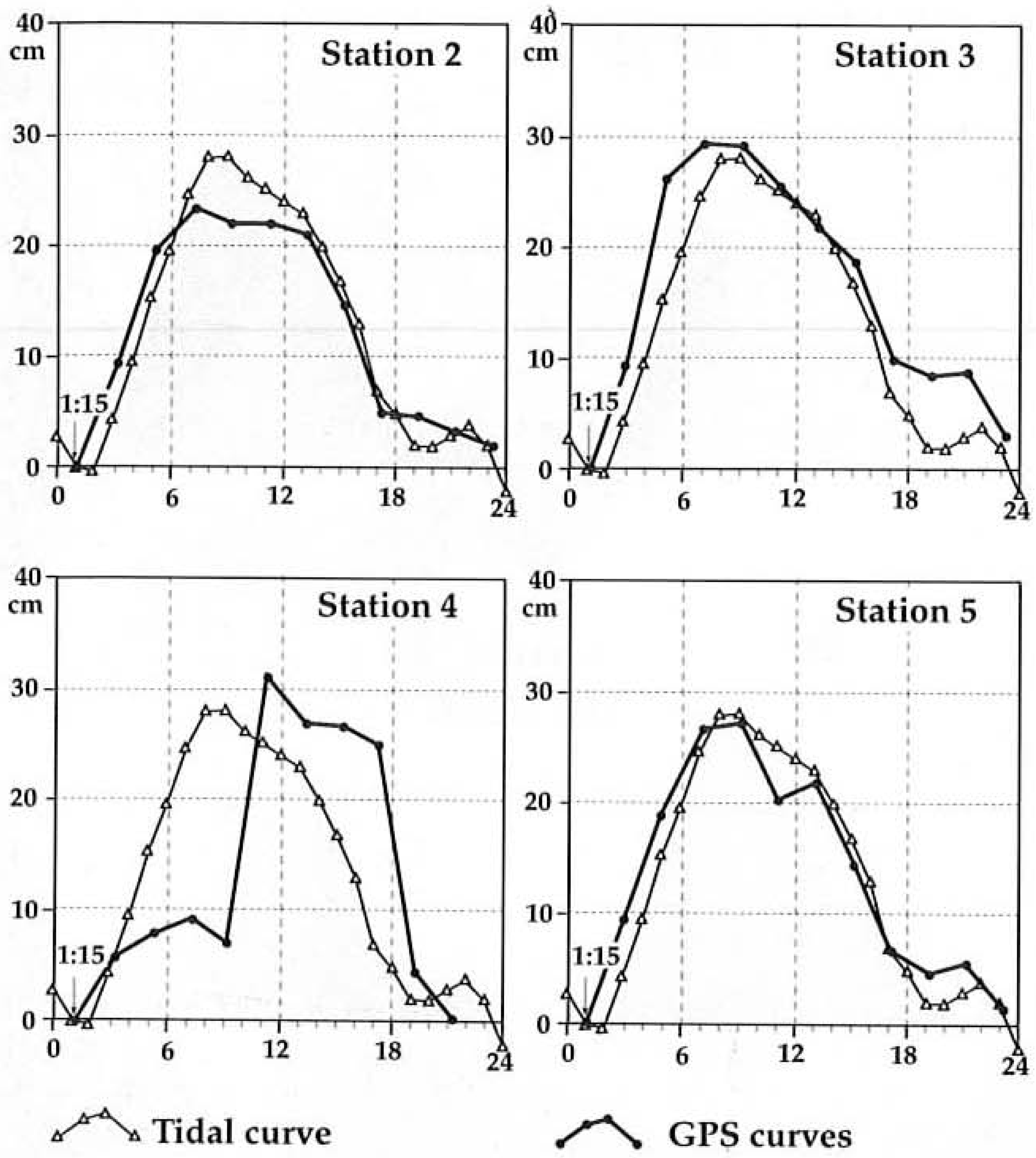


FIG. 3 - Relative vertical movement of Hells Gate Ice Shelf on 5th January 1994 as a function of time for GPS survey stations 2 to 5. The measured tidal curve for the same day near Terra Nova Bay (data from C. Stocchino) is also given as a background (see text for explanation).

## METHODOLOGY OF GPS MEASUREMENTS

The measurements were made simultaneously using four Trimble 4000 SSE and one 4000 SST GPS receivers on the five survey points.

In this experimental phase, kinematic GPS survey was discarded for logistic reasons, since the instruments batteries dit not have the necessary stored energy to cover 24 hours of continuous measurements. A rapid static survey has alternatively been chosen, based on 12 measurements of 30 minutes duration each, at two hours intervals. This technique allows more precise measurements than the kinematic survey, however one must keep in mind the error associated to the movement of the survey station during the 30 minutes of observation. In the present case, this was verified to be in the precision range of the method. Kinematic GPS survey has the potential advantage to tackle the problem of possible high frequency ice shelf oscillations, given the continuous record of height changes. An experiment of kinematic survey measurement of ice shelf oscillations has been performed contemporaneously on Drygalski Glacier by FREZZOTTI & *alii* (1994).

Another important problem, that should be addressed for future measurements, is the possible vertical displacement of the receivers tripods due to ice melting under solar radiation. In the present case, tripods were simply laid on the ice surface and tripods sinking of 10 to 12 cm were observed after the 24 hours measuring session. A mean sinking rate of 0.5 cm/hour was then used to correct the GPS measurements (except for station 1 that was settled on a bedrock promontory), hypothesizing a similar effect at all survey stations. One way to tackle this problem would be to design an instrument holder that could be firmly buried into the ice.

Two different softwares (*GPSurvey* and *Topas Turbo*) were used to elaborate the data. Where data acquisition was not much disturbed (points 2, 3, 5) the two softwares gave similar results. On point 4, however, where data acquisition was strongly disturbed, results were quite different. The noise in data acquisition is most probably linked with ionospheric effects, multipath effects and imaging phenomenon being difficult to invoke in this case. In a peculiar session, *Topas Turbo* gave a float solution, with 29 unresolved cycle slips, while *GPSurvey* gave a fixed solution, that assumes cycle slips resolution. However, the more regular trend of *Topas Turbo* solutions and the strange anomalies of *GPSurvey*, suggest that the *Topas Turbo* algorithm is probably more appropriate where the measurements are strongly disturbed. Therefore, in Antarctica, where a lot of cycle slips exist due to ionospheric noise, this software appears more reliable. The different effects of ionospheric noise on point 4 with respect to the other measurement points could be due to the use of different GPS receivers: a 4000 SST receiver was used on point 4, while 4000 SSE receivers were used on the other points. In fact, in the older 4000 SST receivers the signal squaring technique is used, while in the 4000 SSE receivers a cross-correlation procedure between the two signals, L1 and L2, enables to avoid the signal squaring, that amplifies the noise.

## RESULTS AND DISCUSSION

### *The tidal forcing curve*

In order to provide a base for the interpretation of ice shelf vertical movement curves, it is necessary to know the tidal forcing curve that they should mimic, in a pure hydrostatic equilibrium. Such a tidal curve for the 5$^{th}$ January 1994 was kindly provided by Prof. Carlo Stocchino on the basis of the tide-gauge recordings at Terra Nova Station, about 20 km to the North of Hells Gate Ice Shelf.

### *The GPS curves*

The relative vertical movement of the ice shelf as a function of time is plotted on figure 3 for points 2 to 5. The measured tidal curve is also given as a background. The main features of the curves can be summarized as follows:

a) Curves 2, 3 and 5 show a similar pattern with:

— synchronously peaking values between 7:15 and 9:15, in phase with the maximum of the tidal cycle;

— dissymetric profile, with a regular ascend and a step-like behaviour at the last stages of descend (17:15 to

21:15), in phase with the secondary maximum of the tidal curve.

b) On the longitudinal profile of points 2-3-4, the amplitude of the vertical movement clearly increases upstream.

c) Curve 4, unlike the others, shows:

— a 3-hours time-lag in the achievement of the maximum amplitude;

— a step-like behaviour in the ascending phase, that doesn't exist in the tidal curve;

— a plateau followed by a sharp decrease in the descending phase, whereas the tidal curve shows a more regular gradient.

*Interpretation limits*

Given the conditions of this experimental phase, one must take a certain number of limiting factors into account when interpreting the curves of fig. 3. For example, given the incertitude on the real rate of sinking of tripods at each survey point, differences in amplitude of less than 5 cm for simultaneous measurements on different stations should not be considered as significative. On the other hand, it should be noted that the tidal forcing curve is only strictly valid for Terra Nova Bay, and that coastal configuration, like engulfments and straits, can considerably affect the tidal curve both in amplitude and phase.

*Is the Hells Gate Ice Shelf in full hydrostatic equilibrium?*

Fig. 4 schematically illustrates possible effects of bedrock sides (like, for example, in a fjord or on the flanks of a pinning point) and of bottom topography in the vicinity of the grounding line, on the oscillation of an ice shelf in response to tides. Only the excess hydrostatic pressure due to the tidal forcing is taken into account in the drawings of fig. 4.

Away from any bedrock sides and from the grounding line, the ice shelf will react fully hydrostatically to the tidal forcing (Holdsworth, 1977; Pedley & *alii*, 1986), and the recorded curve for altitudinal changes will mimic the tidal cycle (dashed line on the graphs of fig. 4). Close to bedrock sides, the excess hydrostatic pressure can be splitted into two components: a shear stress parallel to the local bedrock and a tensile (low to high tide) or a compressive (high to low tide) stress perpendicular to the bedrock. The build-up of stresses at the initial stages of ascending and descending tides will set up a delay in the mechanical response of the ice shelf to the tidal forcing. Once a critical value is reached, the energy is released through ice deformation. The GPS curve should then be typically dissymetric with a step-like behaviour just after low tide and high tide. Depending on the geometry of the system (length to height ratio of the ice shelf's cross section; contact area with the bedrock sides) a possible phase-lag could also be observed between the two curves.

Where a hummocky bedrock topography exists, near the grounding line (lower fig. 4-(a)), the GPS curve of a survey station nearby will reflect the combined effects of stress build-up on the local obstacle sides and increasing (low to high tide) or decreasing (high to low tide) decoupling of the glacier from its bed. At rising tide, the delay in the response to tidal forcing due to the stress build-up in the ice will be progressively compensated by the increasing surface area submitted to the excess hydrostatic pressure. Around high tide, full decoupling will eventually occur and the GPS curve will catch up with the tidal cycle. From high to low tide, stress build-up in the ice will slow down the ice shelf response shortly after contact has been recovered with the bedrock bottom topography. Eventually, the ice shelf sinking will follow on during the low tide period. As a result the full GPS curve should also be dissymetric, with a concave rising limb (concavity depending on bedrock obstacles spectrum), a summit in phase with the tide and a multistep-like descending limb.

Curves 2, 3 and 5 from Hells Gate Ice Shelf are in good agreement with the tidal cycle and it can therefore be reasonably estimated that in these survey points the ice shelf is in hydrostatic equilibrium, a necessary condition for ice shelf mass balance calculations from simple dynamical models (Baroni, 1990). Interestingly enough, even the secondary maximum recorded at Baia Terra Nova is present in the three curves. Since this maximum is only a few centimeters high, it gives us confidence in the relatively small error range estimated for the field measurements. The hydrostatic behaviour of point 5 was also unexpected, given its location very close to the shore, in a small engulfment near Cape Confusion. The small size of the catchment feeding the floating ice in this area probably strongly reduces the ice thickness and favours buoyancy very close to the valley side.

On the longitudinal profile of survey stations 2-4, the amplitude of the vertical movement increases upstream. Although the total altitudinal difference of the maximum is only about 10 cm, and could therefore be very close to the interpretation limits, this is coherent with an engulfment increasing effect on the tidal amplitude. Much more striking is the difference in profiles between point 2-3 and point 4. The latter shows departure from an hydrostatic behaviour. This is not surprising given its location in a strait between Vegetation Island and the Northern Foothills. The GPS profile is similar to the one predicted for bedrock side effects (fig. 4-above), adding a phase delay between high tide and maximum ice shelf altitude. However this latter effect could be the expression of tide retardation inland, with regard to the Terra Nova Bay prediction; this may also depend on the *establishment of the port* due to the shape of the Evans Cove engulfment in which the Hells Gate Ice Shelf flows, combined with a *river tide* effect. The GPS curve nevertheless ends up in phase again with the low tide from Terra Nova Bay. The geophysical team working on Hells Gate Ice Shelf placed over the shelf surface, at survey site 4, a microseismic station to test the microseismic activity into the glacial body for a period of 3 days (Caneva & *alii*, 1994a to c; Lozej & *alii*, 1994; Merlanti, personal communication). Intense icequakes activity was detected in restricted periods (about 8 hours) of the day and these result might well be

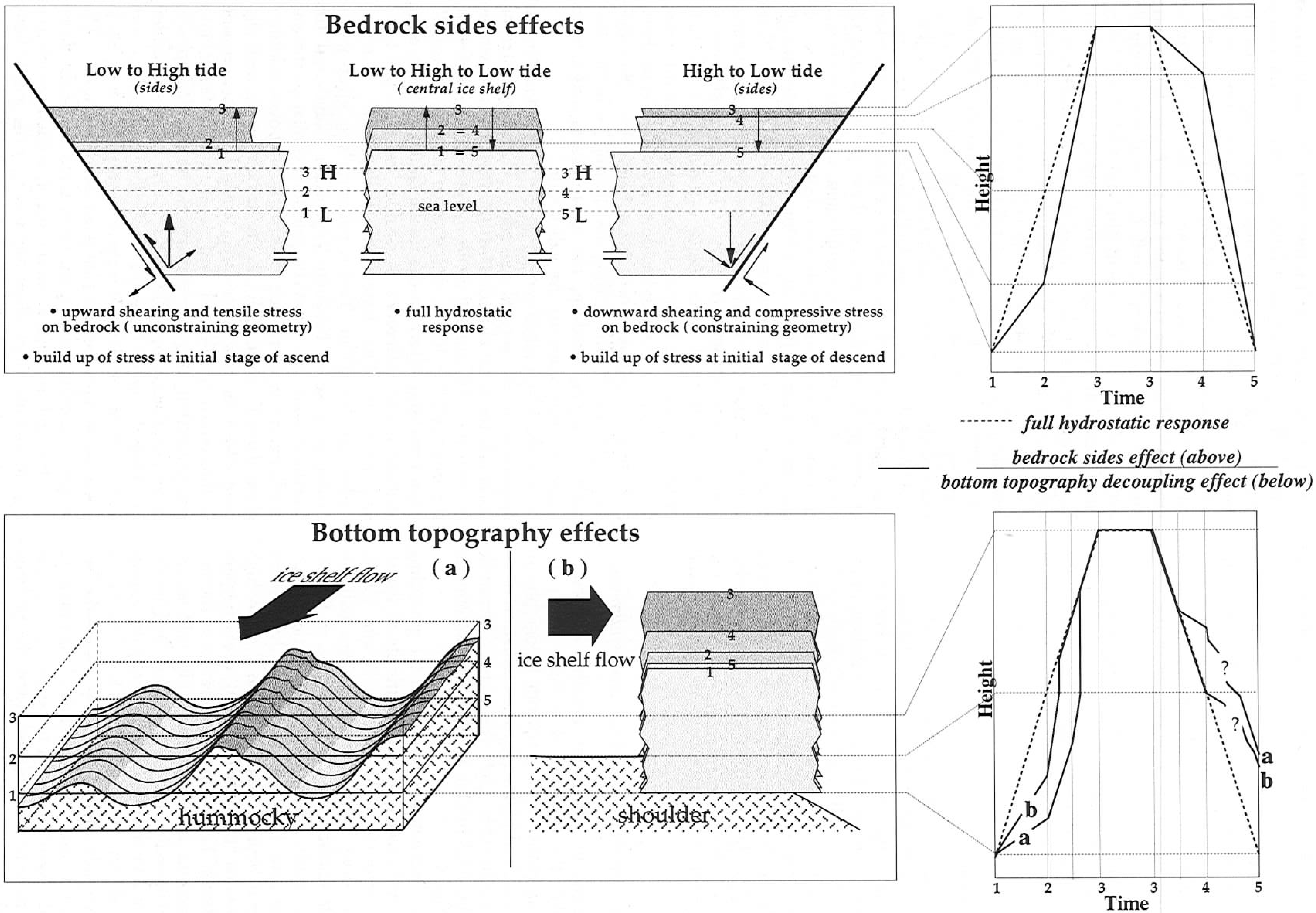


FIG. 4 - Schematic representation of hypothesized bedrock sides and bottom topography effects on the ice shelf's vertical movement. Numbers refer to time steps (1 and 5 = middle of low tide, 3 = middle of high tide, 2 = half time between 1 and 3, 4 = half time between 3 and 5). Shaded areas on the «hummocky bottom topography» correspond to successive areas that would be freed by the ice if there was no mechanical delay.

linked with the stress build-up episodes in the ice. Similar concentrated icequakes activities were reported between high tide and low tide by VAN DER OSTEN-WOLDENBURG (1990) around an ice rumple on Ekström Ice Shelf (Akta Bay, Antarctica).

Vegetation Island thus apparently acts as a pinning point at the level of survey station 4, and the real grounding zone should probably be searched for further upstream in this area.

## CONCLUSION

GPS altitudinal changes records provide us with better insights into the mechanical response of ice shelves to tidal forcing. Beside the possible location of a grounding line where ice shelf oscillation simply breaks down, it shows that there are several possible situations where the ice shelf does not freely respond to hydrostatic pressure changes linked with tides. This would favour the larger concept of grounding «zones» or «areas», as opposed to grounding «lines». GPS studies, coupled with microseismic measurements, could provide valuable informations on the type of dynamic response of the ice shelf to the excess hydrostatic stress applied. The case study of GPS survey station 4 at Hells Gate Ice Shelf suggests that the ice shelf might not always behave elastically in grounding areas, as suggested by PEDLEY & *alii* (1986) but not detected by VAUGHAN (1994).

Future static GPS surveys should rely on improved survey station settings to avoid receivers drift, and test runs should be designed to accurately evaluate advantages and disadvantages of kinematic and rapid static methods. These tests should also focus on a better understanding of software performances in highly disturbed data acquisition situations that seem to occur in Antarctica.

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