Seismic Anisotropy of the Victoria Land Region, Antarctica

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SUMMARY

We present shear-wave splitting results obtained from the analysis of core refracted teleseismic phases recorded by permanent and temporary seismographic stations located in the Victoria Land region (Antarctica). We use an eigenvalue technique to isolate the rotated and shifted shear-wave particle motion, in order to determine the best splitting parameters. Average values show clearly that dominant fast axis direction is NE-SW oriented, in accordance with previous measurements obtained around this zone. Only two stations, OHG and STAR show different orientations, with N-S and NNW-SSE main directions. On the basis of the periodicity of single shear-wave splitting measurements with respect to back-azimuths of events under study, we infer the presence of lateral and vertical changes in the deep anisotropy direction. To test this hypothesis we model waveforms using a cross-convolution technique for the cases of one and two anisotropic layers. We obtain a significant improvement on the misfit in the double layer case for the two stations. For stations where a multi-layer structure does not fit, we investigate lateral anisotropy changes at depth through Fresnel zone computation. We find that anisotropy beneath the Transantarctic Mountains (TAM) is considerably different from that beneath the Ross Sea. This feature influences the measurement distribution for the two permanent stations TNV and VNDA. Our results show a dominant NE-SW direction over the entire region, but other anisotropy directions are present and maybe interpreted in the context of regional tectonics.

Keywords: Antarctica, Mantle Processes, Seismic Anisotropy, Shear-wave Splitting

INTRODUCTION

Splitting of shear-waves from teleseismic earthquakes is a powerful tool to investigate the structure of the upper mantle in different geodynamic environments. Since anisotropy may be a result of deformational events, shear-wave splitting studies permit investigation of the geodynamical processes, which have acted on the area of interest.

Shear-wave splitting is the seismological analogue of optical birefringence. When an S-wave passes through an anisotropic medium, it will be split into two quasi-S waves travelling with different velocities (Savage, 1999). The vibration direction of the faster phase and the difference in arrival time (delay time) between the two phases, are parameters recovered from this analysis. Teleseismic shear-wave splitting of core-refracted phases (e.g. SKS, SKKS) enables the study of the anisotropy located on the station-side of the epicenter-station path. Most of the anisotropy contribution originates in the upper mantle region where olivine is the most abundant mineral (Silver, 1996; Savage, 1999). Since olivine is highly anisotropic, its crystals develop a preferred orientation when a geodynamical process acts. In the simple shear case, Lattice Preferred Orientation (LPO) is generated by dislocation glide (Karato *et al.*, 2008) and [100] crystallographic-axis rotates parallel to the direction of the maximum shear (Savage, 1999) that also corresponds to the faster direction of S-wave vibration direction after splitting. Therefore the study of anisotropy can provide insights into deformational processes which have acted at a regional scale.

The harsh climatic conditions and the inaccessibility of the Antarctic region make it difficult to operate permanent or long-term seismic instrumentation. Few data are available, therefore any additions to the collective dataset are very important in understanding the tectonics of the Antarctic region. In recent years, several studies, which make use of seismic anisotropy, have been carried out, but the overall dataset remains sparse. The current study adds new data and interpretation which improves existing spatial coverage.

In East Antarctica, previous shear-wave splitting studies for the Dronning Maud Land area (Bayer *et al.*, 2007) suggested mainly NE-SW anisotropy direction, with some nearly N-S directions, that authors interpreted as due to crust-mantle coupling deformation. NE-SW is also the main direction for stations located in other inland areas (e.g. at South Pole; Muller, 2001), whereas shear-wave splitting measurements for coastal stations are generally oriented parallel to the coastline as observed for the Lambert Glacier region (Reading and Heintz, 2008). In West Antarctica, NE-SW continues to be the dominant direction beneath the Transantarctic Mountain (TAM) belt (Barklage *et al.*, 2009) and in the Victoria Land region (Pondrelli and Azzara, 1998; Pondrelli *et al.*, 2005). These measurements are interpreted to be related to the TAM uplift, while NW-SE and E-W directions, present sporadically around the Ross Sea, are interpreted as linked to extensional processes which have occurred in the past.

Some studies found also indications of possible two-layer anisotropic structure; Muller (2001) proposed the presence of a two anisotropic layers beneath the Scotia Plate and beneath the western stations of Dronning Maud Land justifying the anisotropy sampled in the upper layer as due to the signature of an Archaean frozen-in anisotropy while the origin of the lower layer would go back to the Gondwana rifting stages. In the Lambert Glacier and Wilkes Land areas, Reading and Heintz (2008) admitted the possible presence of a two-layer structure for coastal stations even if the small amount of data didn't allow modelling the upper mantle anisotropy with the detail obtained by Heintz and Kennet (2006) for the adjacent Australian plate.

In the following, we describe the anisotropy measured for the Victoria Land region, West Antarctica. Using together data recorded at permanent stations VNDA and TNV and data from temporary stations sited around the David Glacier, we show the indications for the presence of different local domains of anisotropy, with a possible double-layer anisotropic system with lateral changes, a configuration more complex than that previously shown for this region. Here we provide an improved study of the regional seismic anisotropy distribution, we identify new heterogeneities and we describe a more detailed Victoria Land structure.

GEOLOGICAL AND GEOPHYSICAL SETTINGS

Antarctica is commonly divided into two main geological domains, East and West, with very different structural and geophysical characteristics (Figure 1). East Antarctica (EA) is classified as a Precambrian craton, the central part of the Palaeozoic Gondwana super-continent. West Antarctica (WA) is interpreted as the assembly of Meso-Cenozoic crustal blocks (Dalziel and Elliot, 1982) or micro-plates with metamorphic and volcanic terranes (Anderson, 1999). The Ross Sea and the West Antarctic Rift System (WARS) are part of West Antarctica and represent the extensional basins developed after Cretaceous and Cenozoic extensions (Behrendt, 1999). Evidence of active alkaline volcanism is present with Mount Erebus and Mount Melbourne volcanoes (Figure 1).

The Transantarctic Mountains (TAM) range separates the East from the West region of the continent. The TAM is a 3500 km long and 200 km wide chain composed, together with the Victoria Land region, of Cambrian and younger rocks. It is considered an intra-continental mountain belt with lack of evidence of compression. Its origin is attributed to an asymmetric uplift of the crust along the Ross embayment flank and subsequent denudation from Cretaceous to Cenozoic time (Fitzgerald, 1992, 1995; Studinger *et al.*, 2004). Fission track analyses (Fitzgerald, 1992) establish the beginning of the main uplift phase at about 50 Ma.

Most of the surface and deeper geological structures of the Victoria Land region can be ascribed to the Ross Orogeny. The Meso-Cenozoic evolution of the Ross Sea has seen two main phases of extension; from 105 to 55 Ma, characterized by E-SE extensional faulting, and from 55 to 32 Ma, generating N-S and NNW-SSE tectonic depression. These extensional phases were followed by right-lateral strike-slip tectonics from 32 Ma to the present.

The tectonic fabric of the crystalline basement also originated during the Ross Orogeny, but in early Palaeozoic times (500-480 Ma). The fabric is defined by steeply dipping metamorphic foliation, highly strained shear zones and fold axial trends, in a main NW-SE direction (Salvini and Storti, 1999). Surface structures in the Victoria Land region can be divided into 3 principal fault systems (Salvini and Storti, 1999). The first one is a NW-SE right-hand strike-slip fault system along which major glaciers stream; the second one is composed by N-S depression profiles interpreted as extensional or transtensional structures associated to Cenozoic, right-lateral shear; the third one includes NE-SW and NNE-SSW faults present in the Terra Nova Bay area, bordering the western shoulder of the Ross Sea, connected to the TAM uplift. Fault directions are parallel to the coastline and tend to rotate to N-S and NW-SE moving towards south.

Several different seismological methods provide structural information which highlights the dramatic discontinuity between East and West Antarctica.

Combining receiver function and phase velocity inversions, Lawrence *et al.* (2006b) derived crustal thickness in various parts of the study region. They show that beneath the Ross Sea the crust is 20 km thick (+- 2 km), and increases to 40 km (+- 2 km) beneath the TAM. A uniform 35 km thick crustal layer characterizes the cratonic domain in East Antarctica. These values are also in agreement with several previous works (Bentley, 1991; Bannister *et al.*, 2003; ten Brink *et al.*, 1997). The crustal structure of northern Victoria Land has been investigated also by Piana Agostinetti *et al.* (2004). Analysing receiver functions they found a 24 km crustal thickness in the Robertson Bay area, with an increase to 31 km westwards of the Transantarctic Mountains (Oates Land). This would suggest that the crustal profile remains approximately stable moving southwards beneath coastal stations, while it changes laterally (at different longitudes). Beneath the stations located in the TAM chain, the authors find evidence of two Moho interfaces between 26 and 48 km in depth.

Another seismological difference between East and West Antarctica concerns shear-wave velocities. The TAM divides a "fast" eastern upper mantle with velocities of 4.5 km/s (typical of a continental shield) from a "slower" western one where velocities decrease to 4.2 km/s (typical for active tectonics and volcanic regions). These values are in agreement also with those inferred from the study of regional surface wave velocities (Danesi and Morelli, 2001; Morelli and Danesi, 2004; Ritzwoller *et al.*, 2001). The transition between West and East occurs at 100 +- 50 km inland near the crest of the TAM (Lawrence *et al.*, 2006c). The same transition separates a colder eastern region from a warmer western one (Lawrence *et al.*, 2006a). The increment in mantle temperature is 200-400 °C (at 80-220 km depth), approximately corresponding to a reduction of 1% in density.

Previous shear-wave splitting measurements in the Victoria Land region and neighbouring areas are shown in Figure 2. Pondrelli *et al.* (2005) measured shear-wave splitting in the northern part of the study area (in purple in Figure 2). Only non-null splitting measurements are plotted on the map and, following the representation of the authors, any measurement is plotted at location corresponding to 150 km of piercing point depth. This procedure is used only with measurements obtained from single event analysis and each measurement is plotted at the surface projection of the ray path at the depth of 150 km. This representation evidences any difference in anisotropy as a function of back-azimuth of studied events, to focus on the possible presence of lateral and vertical changes. The depth choice allows to interpret the total contribution of the anisotropy as located on the upper mantle (Savage, 1999). Near TNV station, measurements have NE-SW dominant fast velocity direction while the average delay time is estimated around 1.6 s. The authors linked this NE-SW direction to the presence of an old cratonic anisotropy and to mantle flows due to the growth of the TAM chain. The other directions (E-W and NW-SE) instead are interpreted as due to the extensional processes associated with the Western Rift system.

Results from the TAMSEIS Project (in yellow in Figure 2) are taken from Barklage *et al.* (2009). They obtained shear-wave splitting teleseismic measurements for 3 temporary arrays (yellow triangles) located principally on the southern part of the Victoria Land and extending inland toward East Antarctica. Splitting parameters are calculated using stacked-waveforms. At the intersections between E-W and N-S arrays, the fast direction is 58° and becomes more E-W towards the coast (67°). The delay time is about 1 sec. At the same intersection, comparing Rayleigh wave phase velocities from different azimuth values, Lawrence *et al.* (2006c) found a fast axis direction ranging between 55° and 85° with magnitude of 1.5-3.0% of anisotropy. In this area, Barklage *et al.* (2009) suggest anisotropy associated with an upper mantle flow related to Cenozoic Ross Sea extension or an edge-driven convection due to the sharp thermal change between West and East Antarctica. Towards the East Antarctica instead the measurements are distributed along a 60° (+- 10°) direction that rotates to 15°-20° (becoming E-W) in two highlands locations (Belgica and Vostok). The main distribution is described as being due to a relict tectonic fabric while the E-W measurements are interpreted as due to different extensional events maybe associated with older tectonic processes.

STATIONS AND DATA

We used data recorded by 11 seismic stations belonging to permanent and temporary networks in the Victoria Land region (Figure 2 and Table S1 on supplementary material). Permanent stations (cyan triangles in Figure 2) TNV and VNDA are located respectively on northern and southern margins of the study region. Both stations are equipped with 3-component broadband sensors (Streckeisen STS-1 and Geoteck KS-54000 Borehole respectively) with free access data availability managed by IRIS consortium (http://www.iris.edu). In the region also temporary stations have been installed. In the course of two expeditions within the Italian Scientific Project PNRA, during the 2003-2004 and 2005-2006 austral summers, we installed 9 broadband temporary seismic stations (blue circles in Figure 2) all equipped with Trillium T40 sensors and powered by solar panels and batteries. All the stations were located around the David Glacier running from the coast to the TAM on both sides of the glacier and cutting the chain perpendicularly, covering an area of 100x150 km^2. One of these stations (STAR, cyan triangle) became permanent at the end of the first expedition and it continues operating.

We analysed records of teleseismic events occurring between 2003 and 2007, with Mw greater than 5.5 and epicentral distance between 85° and 120°. This distance range increases the likelihood of the presence and easy identification of the SKS arrival. These choices allow us to have a dataset for the temporary stations varying from a minimum of 2 months of data (e.g. site MORR) to a maximum of 5 years (site STAR). For both the permanent stations (VNDA and TNV) instead a two-year long dataset is complete.

SINGLE SHEAR-WAVE SPLITTING MEASUREMENTS

The fast axis orientation and the delay time between faster and slower phases are the two parameters provided by shear-wave splitting analysis. Most methods start assuming the anisotropic medium composed by one single layer with horizontal symmetry axis.

The fast velocity direction (ϕ) corresponds to the direction along which strain aligns the minerals; the delay time (dt*)* allows to estimate the thickness of the anisotropic material. We retrieved these two parameters using the Silver and Chan (1991) method. This is based on a grid search over the possible splitting parameters that better remove the effects of anisotropy from the waveforms. In a general case, this can be done searching the most singular covariance matrix based on its eigenvalues λ_1 and λ_2. A special case is when the initial wave polarization is known, as for SKS and SKKS phases, and when the signal-to-noise level is low; in this case the splitting parameters can be recovered minimizing the energy on the transverse component.

We used the SPLITLab environment (Wustefeld *et al.*, 2008), a Matlab graphical user interface (GUI) that enables the analysis of shear-wave splitting for large volumes of data and a quick quality check on the results. In addition, SPLITLab provides a method to calculate simultaneously shear-wave splitting parameters using the eigenvalue approach (EV), minimization of energy on the transverse component (SC, notation from Wustefeld *et al*., 2008) and rotation-correlation technique (RC) (Fukao, 1984; Bowman and Ando, 1987) that removes the effect of splitting, maximizing the cross-correlation coefficient between radial (Q) and transverse (T) components of the waveforms in the selected windows.

As the initial polarization of the wave is assumed to be radial, RC and SC methods are applicable to phases as SKS and SKKS; the EV method instead uses the back-azimuth as initial wave polarization and therefore it is applicable only for S phases. Synthetic tests on the RC and SC methods (Wustefeld and Bokelmann, 2007) demonstrate comparable results when the fast axis is far enough from the back-azimuth direction but show very different behaviours when the back-azimuth is close to the fast or slow direction (null directions). In this cases, the RC method deviates by 45º from the input fast axis, while the SC method yields scattered estimates around it. Therefore a comparison of results between these two methods distinguishes null measurements from the real splitting cases and allows us to assign a quality flag for any single measurement (Wustefeld and Bokelmann, 2007).

More specifically, we define the following parameters:

$\Delta\Phi=\Phi_{SC}-\Phi_{RC}$ and

$\rho=dt_{RC}/dt_{SC}$.

and we pick "true" splitting measurements only if the following conditions are satisfied simultaneously:

1) $\rho>0.7$

2) $|\Delta\Phi| < 22.5^{\circ}$

3) Signal-to-noise ratio (SNR) on the transverse component greater than 3

The measurement is flagged as "good" when $\Delta\Phi<8^{\circ}$ and $0.8<\rho<1.1$, "fair" when $\Delta\Phi<15^{\circ}$ and $0.7<\rho<1.2$ and "poor" in all other cases.

We consider null a measurement when an S-wave travelling through the medium has no splitting. This happens when the medium is isotropic or when the wave propagates along the so called null direction, that is the direction for which the initial wave polarization is parallel to the fast or slow axis (Savage, 1999). For SKS and SKKS cases, these directions coincide with the back-azimuth of the selected event. As suggested by Wustefeld and Bokelmann (2007), we can consider a measurement null when $\Delta\Phi \sim n*45^{\circ}$ (with n an integer) and small ρ; we consider "good nulls" when $37^{\circ}<\Delta\Phi<53^{\circ}$ and $0<\rho<0.2$, "fair nulls" when $32^{\circ}<\Delta\Phi<58^{\circ}$ and $0<\rho<0.3$ and "poor nulls" in all other cases or when the SNR is lower than 3.

In the following we will consider only the SC measurements and we compare them with the results of the RC method for the quality assignment only.

Single station-event measurements obtained with the Silver and Chan (1991) method are shown on the map in Figure 3 and listed in Table S2 (splitting measurements) and Table S3 (null measurements) of the supplementary materials. For the sake of simplicity, in red we have plotted measurements flagged as “good” and in orange those flagged as “fair”; all measurements are projected at a piercing point of 150 km depth to enhance any lateral variation in the anisotropy distribution beneath the station.

In total, we have 94 good and 44 fair splitting and 33 good and 37 fair null measurements. The distribution of the orientation of these measurements is very scattered (Figure 3). NNE-SSW seems to be the most frequent fast direction, but also NNW-SSE or N-S measurements are well visible. For some stations we have measurements perpendicular to each other as an expression of the possible presence of a complex anisotropic structure beneath the region. Nulls measurement distribution is in agreement with this single-splitting pattern.

The distribution of average values of splitting measurements, were calculated for single stations (Figure 4 and Table S4). When possible, the average values were calculated using good and fair measurements (dark blue segments) but in a few cases only fair measurements were used (cyan segments). In all cases nulls are excluded. Due to lack of results, caused by the few time of recordings and noisy data, in JYCE and MORR no average measurement is calculated. Most of the stations (TNV, VNDA, TRIO, HUGH) show a NE-SW direction and delay time values mostly compare well among them and in agreement with previous works. Station STAR has average fast axis with a NNW-SSE fast direction while in OHG the fast direction is N-S with a lower value of delay time. Stations with average anisotropy direction calculated with fair measurements (PHIL, PRST, and MDAN) show a uniform NNE-SSW direction, quite different with respect to surrounding stations.

The distribution of the measurements directions is comparable with previous works (Barklage *et* *al.*, 2009; Pondrelli *et al.*, 2005). Our results however seem to estimate larger values of delay time; in fact, compared to the average values of 1 and 1.6 s calculated in the past, for most of our stations we also find values larger than 2 s and only at OHG we have a smaller delay time (1.5 s). This could be explained considering that we keep into account measurements until 4 s of delay time while the maximum value in Pondrelli *et al.* (2005) is 3 s providing smaller mean value. With respect to measurements in Barklage *et al.* (2009), instead, the difference is intrinsic in the calculation methods, given that in this last case the splitting parameters are calculated stacking waveforms for each station. In the next section, we will see that our mean values are comparable with those of this last work when we use a comparable method (as for example the cross-convolution technique).

VERTICAL CHANGES OF THE ANISOTROPY

The transverse energy minimization (SC) and rotation-correlation (RC) techniques described above allow the calculation of the splitting parameters based on two main assumptions concerning the structure of the anisotropic medium to analyse. The anisotropic medium is supposed to have one single anisotropic layer with anisotropy oriented along its horizontal axis. The splitting parameters provide a true value if the earth structure is well-drawn by the assumed model, while they give an "apparent" result if the real earth structure beneath the study site includes two or more anisotropic layers or the symmetry axis is not horizontal. A periodicity of the splitting parameters pattern with respect to the back-azimuth of the events usually indicates the presence of greater complexity (Savage, 1999; Menke and Levin, 2003).

In order to provide a possible interpretation to the variations that we obtain in our measurements, we studied the distribution of splitting parameters with respect to the back-azimuth of teleseismic earthquakes. Examples for VNDA, STAR and TNV are shown on Figure 5. Good (red crosses) and fair (blue crosses) splitting measurements and good (red circles) and fair (blue squares) null measures are displayed. The distribution of fast axis and delay time with respect to the back-azimuth seems to fit with different types of two-layer models (represented by green lines). The distribution of earthquake’s back-azimuth is however discontinuous; for most events, phases under study come from NW or SE quadrants while the other back-azimuths are absent. Therefore a unique interpretation would be unreliable.

To test the vertical variation of anisotropy in a different way, we use a cross-convolution technique (Menke and Levin, 2003) to model all waveforms simultaneously and re-build the complex pattern of our measurements; we try to fit the data with an adequate two-layer model.

The technique consists of two steps; first, splitting parameters for each event are calculated maximising the cross-correlation between horizontal rotated seismograms. Only events with a cross-correlation estimator value greater than 0.8 and modelled polarization within the error range of 20°, are picked for the following step. These criteria are so selective that only a small portion of data can be used for the inversion, generally about 8-9% of the complete dataset for each station. For this reason the inversion was carried out only for permanent stations TNV and VNDA and for those temporary stations having a wide range of day-recordings, namely STAR and OHG. The final solutions have been obtained using a minimum of 4 (OHG) and a maximum of 24 (VNDA) events.

In the second step we find the unique earth model structure that satisfies the entire group of observations with a grid-search inversion using a cross-convolution technique. Results are represented as an error surface plot as showed on Figure 6. The more complex model is chosen considering the distribution of the models on error surface plots and on the misfit reduction. In the example, therefore, for TNV the one-layer model is chosen as the best fitting whereas the two-layer model seems to be the best for OHG. Where the best solution is a double layer model, the final solution is selected by excluding those with a delay time greater than or equal to 3.0 sec and differences between two layer fast axis orientations ranging between 80° and 100°. This choice avoids near-normal fast polarization values whereby delay time in one layer cancels the delay time in the other (Menke and Levin, 2003).

The modelling results are displayed on the map in Figure 4 and listed in Table S5 (supplementary material). Solutions for stations where a one layer earth structure fits the waveforms better than a double-layer model are shown with the violet lines oriented parallel to the fast axis and scaled accordingly to the delay time. Stations for which the double layer is the best model are represented with two colours: red for the lower and black for the upper layer. For each station the 10 solutions with lowest misfit are plotted.

Beneath VNDA and TNV stations, located respectively on the southern and northern margin of the region, a vertical variation of the anisotropy is absent. From the inversion we deduced that beneath TNV the dominant anisotropy shows a fast direction between 41° and 44° and delay time between 1.1 and 1.2 s. For VNDA the situation is similar, with a fast direction between 36° and 39° and delay time ranging between 1.0 to 1.1 s. These values are consistent with the NE-SW alignment found for the averaged measurements and with previous papers.

Beneath STAR and OHG we infer that a two layer structure provides a best fit to the available data. These sites are located on structurally different places: STAR is sited along the coast, in an area where magma injection intruded along the Cenozoic N-S trending master faults (Rossetti *et al.*, 2000) while OHG is located inland, on the eastern shoulder of Prine Albert Mountains, characterized by pre-Cenozoic basements (Rossetti *et al.*, 2000). Nevertheless, the anisotropy shows similar patterns. Underneath STAR the fast axis for the lower layer varies from 100° to 150° and delay time from 0.9 to 2.3 s; in the upper layer respective intervals are -10° to 40° and

0.9 to 2.2 s. Beneath OHG, the fast axis direction for the lower layer varies in the range from 120° to 150°, time delay from 1.2 to 1.6 s; for the upper layer fast axis directions are from -10° to 20° and time delay from 1.7 to 2.9 s. All these measurements are mutually consistent and close stations show similar fast-axis orientation for the upper layers (black lines).

LATERAL CHANGES IN THE ANISOTROPY DIRECTION

Results obtained for the two permanent stations TNV and VNDA show scattering in the single event-station measurements, but absence of evidence for multi-layer structure. We hence investigate on the hypothesis of lateral changes of the anisotropy direction at depth as a possible interpretation of our measurements.

The computation of Fresnel zones, such as suggested by Alsina and Snieder (1995), helps to identify the presence of different patterns of anisotropy sampled from rays coming to the same station from different back-azimuths. Taking into account where the rays have a common path beneath the station it is possible to identify the depth interval at which this change occurs (Figure 7).

The disturbance generated by an earthquake is influenced by physical properties of the earth in the vicinity of the geometrical ray path between source and receiver. This ray path can be approximated as a tube, the diameter of which is the Fresnel zone. The size of the Fresnel zone is a function of the wave frequency, and distance along the ray. For a steep-incidence phase, such as SKS or SKKS, it is approximately proportional to the depth beneath the receiver. The Fresnel zone at the depth *h,* can be calculated using (Pearce and Mittleman, 2002):

$$R_f = \frac{1}{2}\sqrt{T\nu h}$$

where R_f is the radius of the Fresnel zone expressed in km, T is the dominant period of the wave and ν is the wave velocity. We choose T=10 s as the dominant period of the wave, with the corresponding shear-wave velocity of S phase obtained from IASP91 model (3.75 km/s at 35 km, 4.476 km/s at 50 km, 4.49 km/s at 100 km, 4.45km/s at 150 km, 4.5 km/s at 200 km and 4.6 km/s at 250 km).

Examples for VNDA and TNV stations are shown in Figure 7; for each station we mapped the shear-wave splitting direction obtained studying two events coming from opposite back-azimuths. The two rays visibly sample different anisotropic patterns. If we take into account that these two rays share the same path beneath the station (see sketch included in Figure 7), the lateral change in the anisotropy should lay deeper than their conjunction point (Z depth on the inset). Indeed, below this depth the rays sample different regions of the upper mantle (blue circles on Figure 7) and above this depth the rays travel through the same anisotropic medium (yellow circles). The Fresnel zones are calculated for 35, 50, 100, 150, 200, 250 km of depth. Shared paths are represented by intersecting circles following opposite rays, vice versa paths along which rays are separated (thus, sampling different regions) are represented by non-crossing circles. The boundary between crossing and separated circles defines the depth at which the lateral variation occurs. We can deduce that for VNDA the lateral variation on the anisotropic properties occurs between 50 and 100 km of depth (last crossing and first separated circles respectively) while beneath TNV it occurs between 100 and 150 km of depth.

When we analyse rays coming from NW at both permanent stations, we obtain similar results, which indicate a dominant NE-SW anisotropy direction beneath the TAM. This is the most frequently measured direction for the region with no dependency on the recovery method.

On the contrary, rays coming from east seem to sample different anisotropic structures at the two sites - WNW-ESE for TNV and NW-SE for VNDA. These observations indicate two distinct anisotropic characters in the TAM and the Ross Sea Embayment.

DISCUSSION

Figure 8 summarizes all our shear-wave splitting results (in colour) in the Victoria Land zone; for comparison we add measurements obtained by previous studies (in grey). The figure indicates the presence of different domains of anisotropy between margins and central part of the Victoria Land region.

At station TNV (northern region) we have a general agreement between different measurements. The NE-SW trend found by Pondrelli *et al.* (2005) and lately confirmed by Barklage *et al.* (2009) is in agreement with both our average of single measurements (blue stick) and our group inversion model (violet stick). Our last analysis suggests that the scattering in single measurements should not be ascribed to a vertical change in the anisotropy direction, at least at lithosphere-asthenosphere structure scale. The Fresnel zone computation shows that a lateral variation in anisotropic character at depth beneath TNV explains the splitting directions moving away from the dominant NE-SW.

In the southern region we have a similar situation. Our results for VNDA station are consistent and also agree with the splitting directions obtained for the temporary TAMSEIS network (in gray). The NE-SW direction is generally confirmed for stations moving towards the north. Again, the group inversion using our data excludes a vertical change in anisotropy directions beneath VNDA (at least at the scale we can investigate), while our Fresnel zone analysis supports the possibility of a lateral change at depth. This allows us to explain the single measurements trending away from the main NE-SW direction.

Some estimates for the thickness of the anisotropic layer in the area can be inferred from delay time values of the grouped inversions. In both North and South Victoria Land, delay times range between 1.0 to 1.2 s. Given that Lawrence *et al.* (2006c) estimate 1 s delay time for a 150 km thick anisotropic medium, with 3% anisotropy, we infer that the thickness of the anisotropic layer should vary between 150 and 180 km.

From the calculation of the Fresnel zone, we can affirm that the anisotropic material should lay at a depth larger than 50-100 km (smaller values obtained respectively for VNDA and TNV), therefore the anisotropy thickness become in general greater than 200 km in depth. Since the lithosphere thickness beneath the Ross embayment was calculated in 250 km (Morelli and Danesi, 2004), anisotropy would be partially located in the lower lithosphere, with a possible contribution to the asthenospheric mantle.

The central part of the region has different features. The first difference is the direction of average fast axis measurements in OHG and STAR, which are N-S and NNW-SSE respectively. The mean directions calculated using only fair measurements (light blue stick on Figure 8) follow the same pattern.

Group inversion here gives a two-layer anisotropic model with NW-SE direction for the lower layer and N-S for the upper one. Since OHG is located on thick crust (about 35 km; Lawrence *et al.*, 2006c) and STAR on thinner crust (about 20 km), and considering that the anisotropy direction shows the same pattern, it is reasonable to expect that the anisotropy distribution is independent from the shallower structure, excluding (or limiting) a possible crustal contribution. Delay time values vary between 1.2-1.6 s and 0.9-2.3 s in the lower layers and between 1.7-2.9 and 0.9-2.2 s in upper ones for OHG and STAR respectively, providing estimates for anisotropy thickness of 435-675 km beneath OHG and 270-675 km beneath STAR. Considering that the lithosphere thickness is approximately 250 km, we infer an asthenospheric contribution.

From these results it appears that a narrow zone (approximately 100-150 km) separates a dominant NE-SW anisotropy of the northern and southern areas from the double layer structure inferred for stations closer to the David Glacier. Dominant directions for upper and lower layers are N-S and NW-SE respectively. The first orientation is in agreement with results found at some stations of the TAMSEIS array (gray lines on Figure 8) while the second direction matches with some single measurements close to station TNV (gray lines on Figure 8; Pondrelli *et al.*, 2005). TRIO and HUGH, temporary stations located in the central part of the study region, have a NE-SW mean value. On these sites however we could not apply group inversion or the Fresnel zone technique for lack of usable data.

Our measurements of anisotropy can be easily related to the tectonic features in the area, which indicate that crust and sub-continental mantle deform coherently (Vertically Coherent Deformation, VCD, as defined by Silver, 1996). The basic idea is that when more than one deformational event occurs, the effect of the younger is recorded on the hotter and deeper layer, while the oldest event remains recorded in the shallower and colder layer. With this concept in mind, we interpret the double layer anisotropic structure: the N-S direction of shallow anisotropy would be related to the deformation occurred during the second phase of extension (55-32 Ma), and the lower layer anisotropy would be related to the last transtensional event, that is still going on (32 Ma to the Present). In this context the NE-SW anisotropy can be interpreted as frozen-in anisotropy relative to older geological events as inferred by several authors (Pondrelli *et al.*, 2005; Barklage *et al.*, 2009), overprinted locally by more recent tectonic events. This hypothesis would also agree with possible lateral variations at depth. In fact, the contribution from western paths is in agreement with the NE-SW frozen-in anisotropy that would be beneath the TAM chain. More recent tectonic events have been taking place mainly in the Ross Sea, beneath which we sample WNW-ESE to N-S anisotropy directions.

Our measurements could also indicate an absolute plate motion (APM) contribution. The APM for the Antarctic plate on the Victoria Land region is 18° from N (green arrow on Figure 8; Gripp and Gordon, 2002) that is quite similar to the lower layer anisotropy direction. We therefore could deduce that the frozen-in anisotropy existing in the upper layer is linked to the two extensional phases of the Ross Orogeny and the APM contribution is constrained to exist in the lower layers. This hypothesis has been already investigated by Kendall *et al.* (2002) studying seismic anisotropy in continental environments as the Canadian shield. However, the low velocity of the Antarctic plate (1.3-1.6 mm/yr) does not produce necessarily the strain needed to generate this amount of anisotropy. Therefore, in agreement with Barklage *et al.* (2009), we suggest that this mechanism is not likely to be significant in the region that has been investigated in this study.

CONCLUSIONS

Shear-wave splitting measured in the Victoria Land region indicates that the NE-SW anisotropic direction is the most frequent orientation of anisotropy for stations located on northern and southern domains of the study region, in agreement with previous measurements. Here we add some new data supporting the presence of a lateral variation at depth, represented by a mainly NE-SW anisotropy direction beneath the TAM and some indications of a WNW-ESE to NW-SE anisotropy beneath the Ross Sea. For stations located around the David Glacier the distribution of single measurements is more scattered and the grouped inversion is consistent with the presence of a double anisotropic layer for the central area of the Victoria Land. The two dominant directions are N-S and NNW-SSE for the upper and lower layer respectively, in agreement with the direction of most of the tectonic structures in the area, presumably generated during the Ross Orogeny deformational phases.

This work has provided improved insights into the regional seismic anisotropy pattern, including newly identified heterogeneities and a more detailed picture of the structure of Victoria Land. Continued improvements to the database in the course of new field campaigns will allow further refinement of these results.

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the GMT package (Wessel and Smith, 1991; Wessel and Smith, 1998).

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FIGURE CAPTIONS

Figure 1: Map showing the elevation of the bedrock (Lythe *et al.*, 2001) in Antarctica and main structural and seismic regions. The zoomed map corresponds to the Victoria Land region.

Figure 2: Map showing broadband seismic stations operating in the Victoria Land region; cyan triangles are permanent stations (TNV, VNDA and STAR), blue circles are temporary stations. Yellow triangles represent the TAMSEIS project stations. In the same map previous shear-wave splitting measurements are shown; lines are oriented parallel to the fast axis with lengths proportional to delay time. Purple lines are results from Pondrelli *et al.* (2005) plotted for 150 km deep piercing points; yellow lines are results from Barklage *et al.* (2009) plotted at the surface.

Figure 3: Single splitting (map on the left) and null (map on the right) measurements obtained using the method of Silver and Chan (1991). In both maps good (red) and fair (orange) measurements are plotted using a piercing point of 150 km. Splitting measurements are plotted with line-segment oriented parallel to the fast axis with lengths proportional to delay time; null measurements are plotted with two cross-line oriented parallel to the back-azimuth and perpendicular to it. Blue circles and cyan triangles show locations (see Figure 2 for colour legend).

Figure 4: Average measurements (dark blue and cyan) and results of the inversion (violet and

red-black lines) calculated for each station. Average measurements: results in blue are calculated using good and fair measurements while those in cyan are obtained with only fair measurements. Grouped Inversion: for each station the 10 best solutions, with lowest misfit, are plotted. Violet lines represent one-layer best fitting model measures. Red and black lines respectively indicate lower and upper measures for two-layer best fitting models.

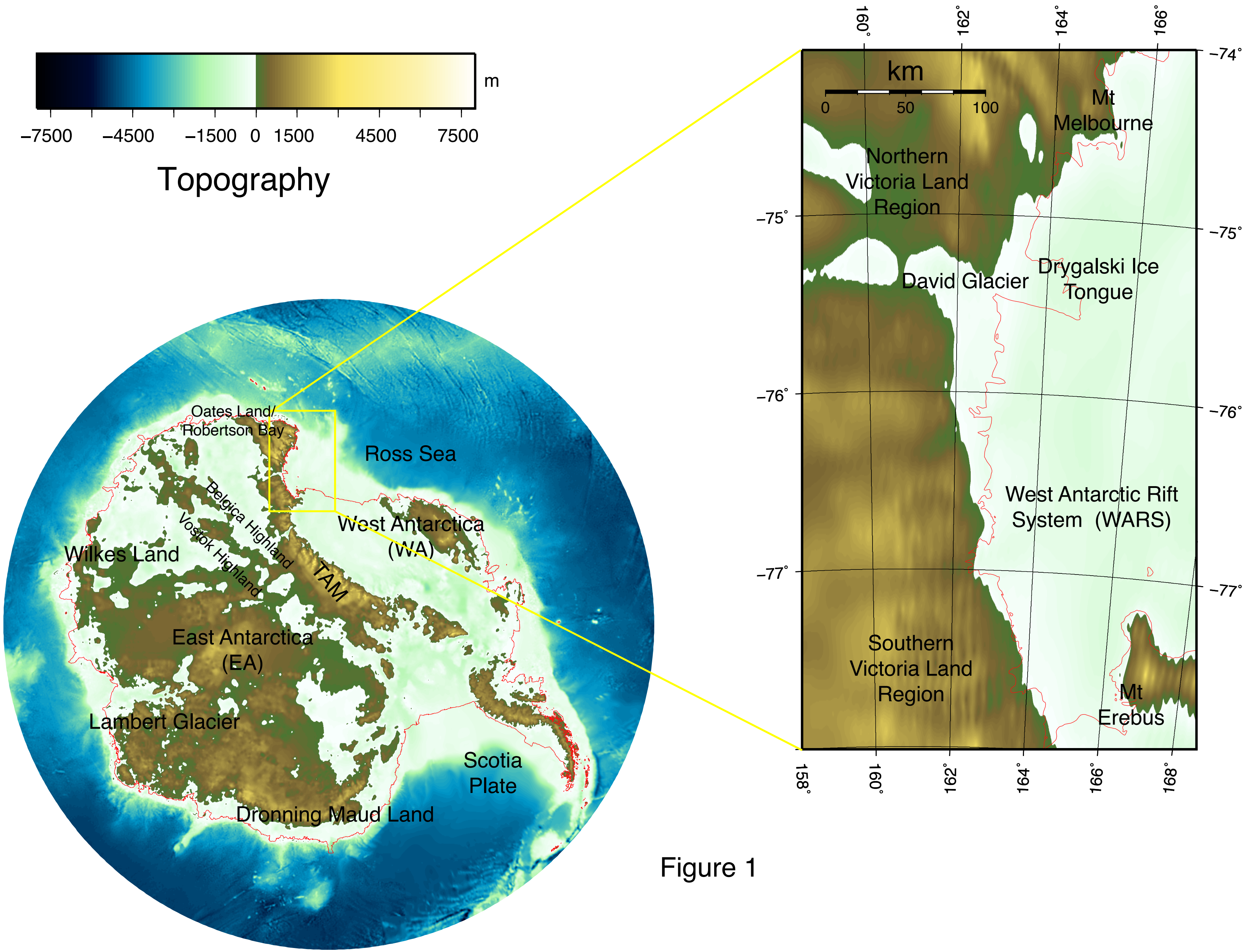
Figure 5: Examples of back-azimuth dependence of the splitting parameters for VNDA, STAR and TNV stations. Each panel contains good (red crosses) and fair (blue crosses) split measurements and good (red circle) and fair (blue square) nulls measurements. Poor results are excluded. Green lines on upper and medium panels correspond to the theoretical distribution of two-layer model with splitting parameters described above each figure. The distribution of single measurements is showed on lower plots.

Figure 6: Examples of error surface plots calculated in the grouped inversion for TNV and OHG stations in one (a and c) and two layers (b and d) cases. a,c) The white star indicates the minimum misfit error model. b,d) In white all regions where errors are greater than the one layer estimator; coloured areas correspond to regions where errors are smaller for the two-layer case. The two blue crossing-lines correspond to the one layer model solution. Green star is the lowest error misfit model.

Figure 7: Examples of Fresnel zones analysis for TNV and VNDA. Two events with opposite back-azimuth and different splitting parameters are analysed. Different size on the circles

corresponds respectively to 35, 50, 100, 150, 200, 250 km of depth of the Fresnel zone. In red we show the splitting measurements plotted at 35 km of depth. All intersecting circles in yellow represent the depth (Z on the inset) above which rays sampled the same anisotropy; in blue, separated circles define the depth below which rays sampled mediums with different anisotropic properties.

Figure 8: Summary map of shear-wave splitting results. Mean values of the single shear-wave splitting, calculated using good and fair split measurements, are in dark blue; mean values calculated with only fair measurements are in light blue; results from group inversion where the best model is the single one (10 better solutions) are in violet; red and black are 10 better solutions for lower and upper layer respectively. Previous results of Pondrelli *et al.* (2005) and Barklage *et al.* (2009) are plotted in grey. The big green arrow indicates the absolute plate motion of the Antarctica plate (Gripp and Gordon, 2002). Crustal thickness is taken from Lawrence *et al.* (2006b).



m
–7500
–4500
–1500
0
1500
4500
7500
Topography
Oates Land/
Robertson Bay
Ross Sea
Belgica Highland
Vostok Highland
West Antarctica
(WA)
Wilkes Land
TAM
East Antarctica
(EA)
Lambert Glacier
Scotia
Plate
Dronning Maud Land
km
0
50
100
Mt
Melbourne
Northern
Victoria Land
Region
David Glacier
Drygalski Ice
Tongue
West Antarctic Rift
System (WARS)
Southern
Victoria Land
Region
Mt
Erebus
160°
162°
164°
166°
158°
168°
–74°
–75°
–76°
–77°

Figure 1

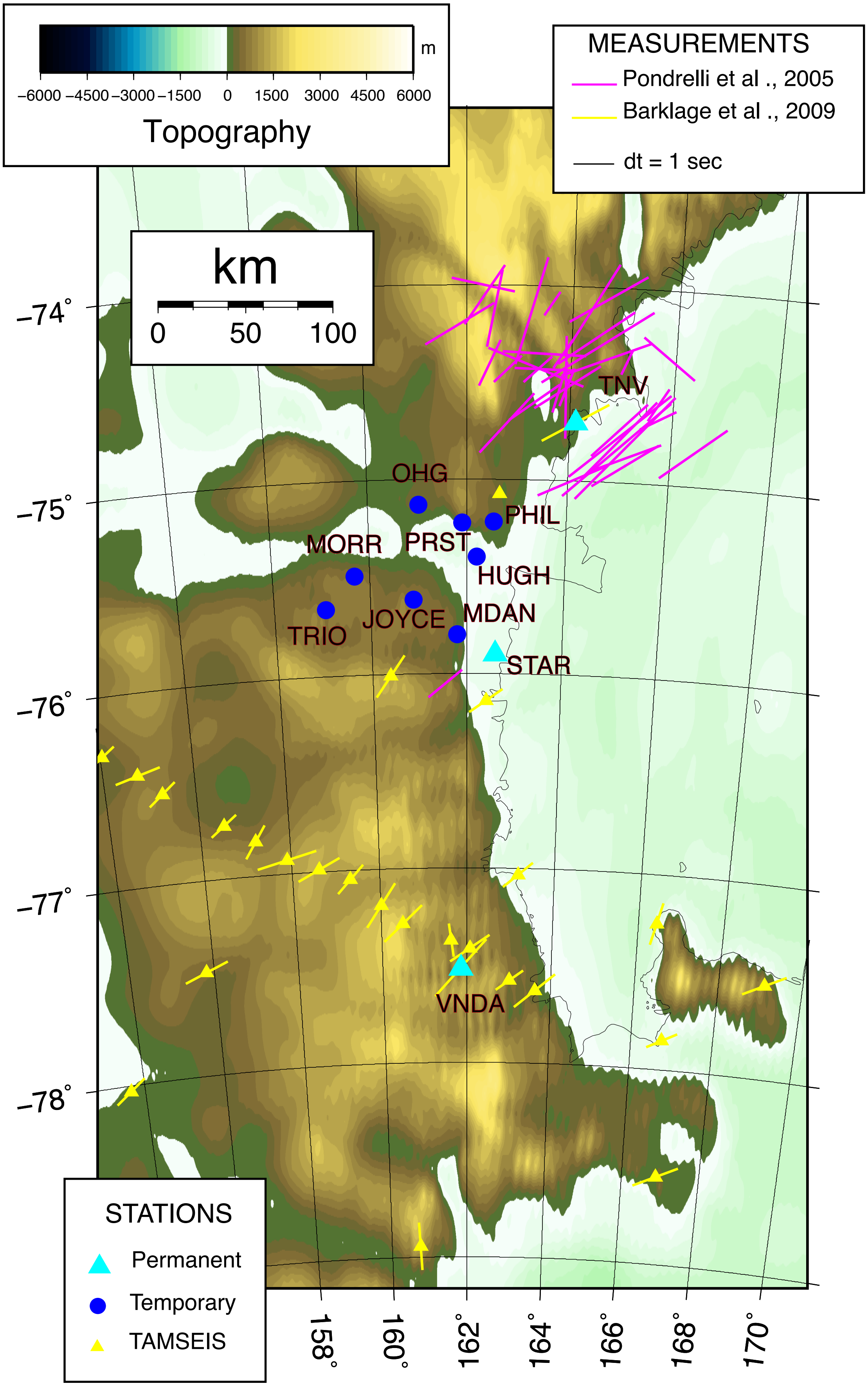
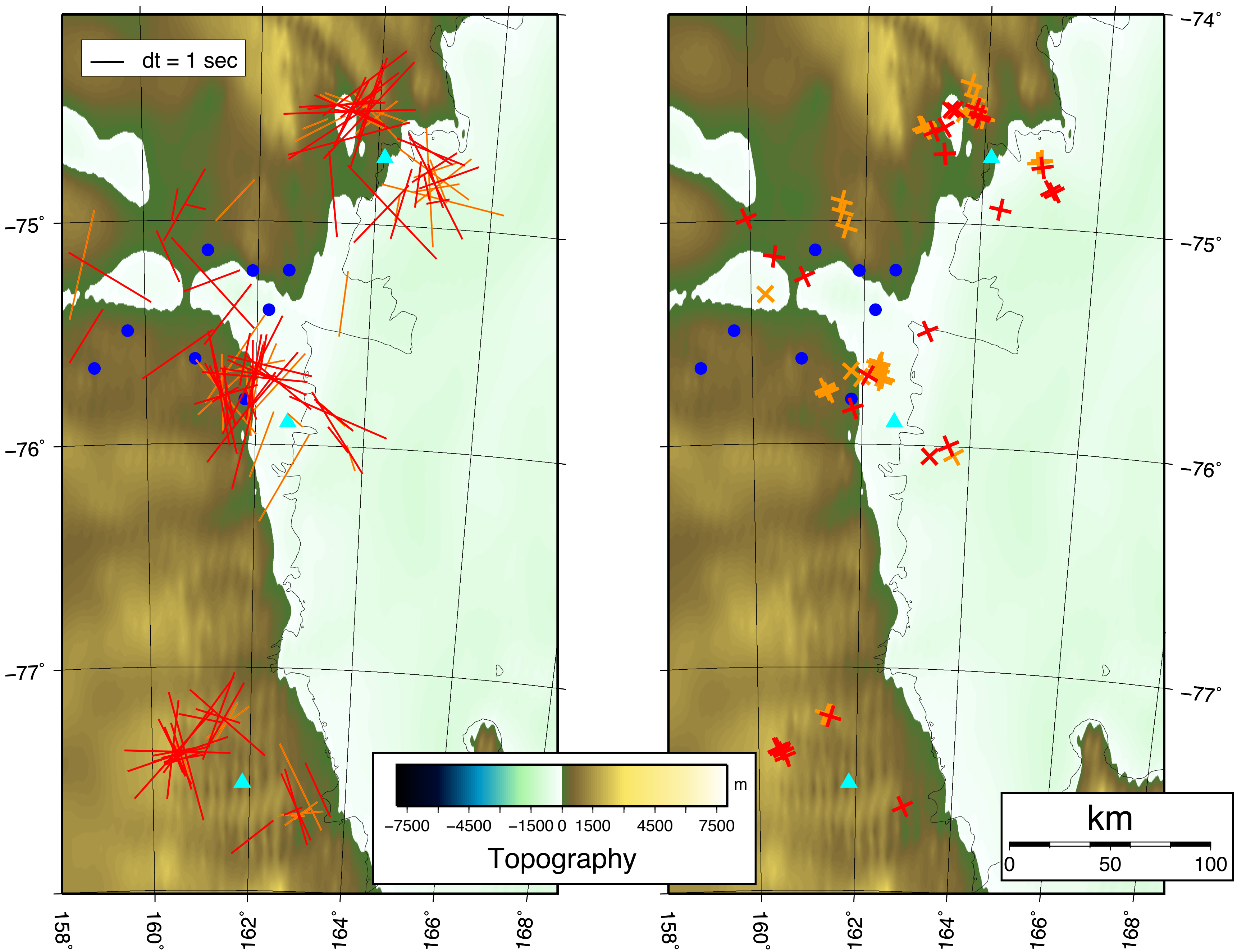

Topography
m
−6000 −4500 −3000 −1500 0 1500 3000 4500 6000
km
0 50 100
MEASUREMENTS
Pondrelli et al ., 2005
Barklage et al ., 2009
dt = 1 sec
TNV
OHG
PHIL
PRST
MORR
HUGH
JOYCE
TRIO
MDAN
STAR
VNDA
−74°
−75°
−76°
−77°
−78°
158°
160°
162°
164°
166°
168°
170°
STATIONS
Permanent
Temporary
TAMSEIS

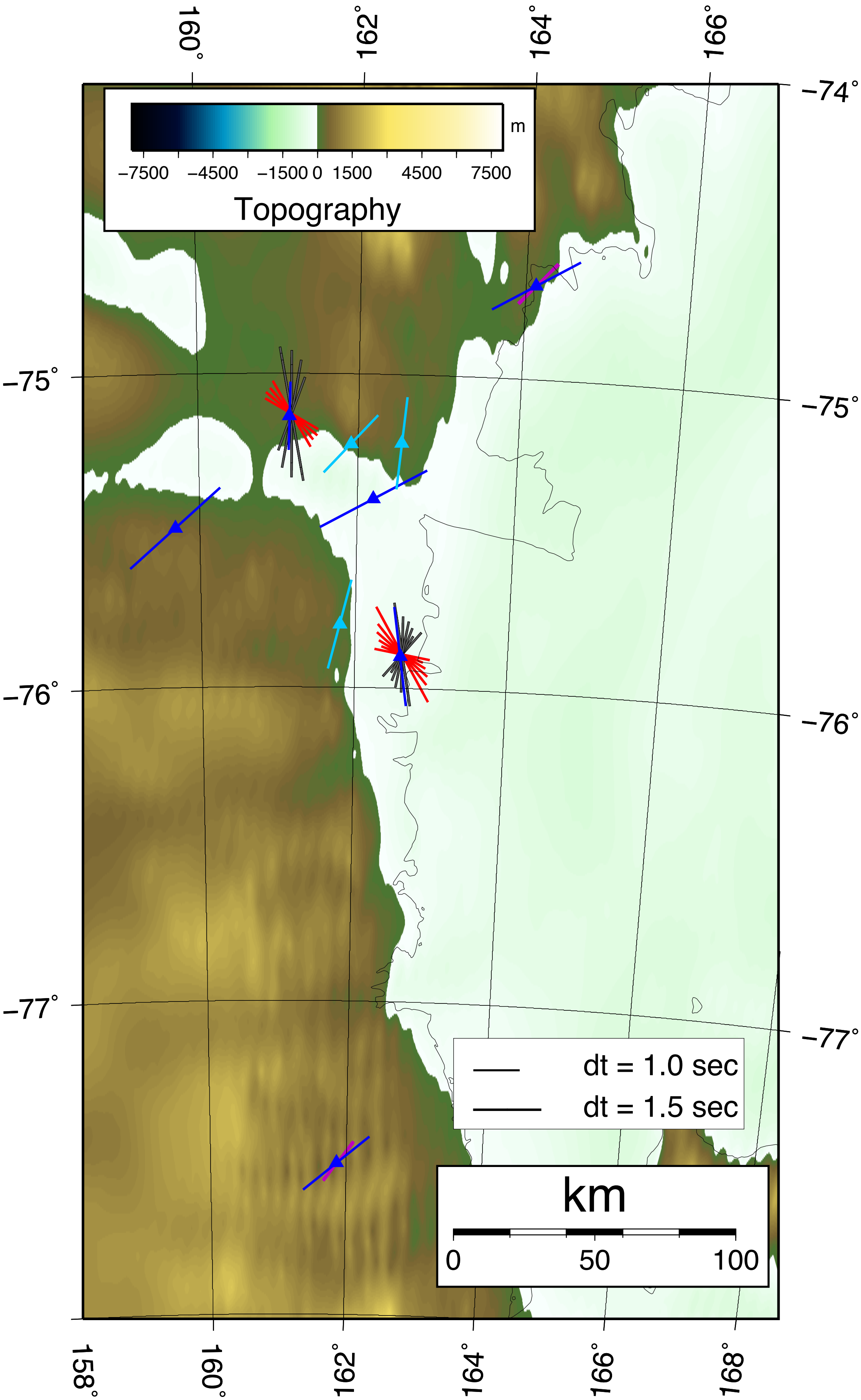
Figure 2



dt = 1 sec
−74°
−75°
−76°
−77°
158°
160°
162°
164°
166°
168°
m
−7500
−4500
−1500
0
1500
4500
7500
Topography
km
0
50
100

Figure 3

Figure 4



160°
162°
164°
166°
−74°
−75°
−76°
−77°
m
−7500
−4500
−1500
0
1500
4500
7500
Topography
dt = 1.0 sec
dt = 1.5 sec
km
0
50
100
158°
160°
162°
164°
166°
168°

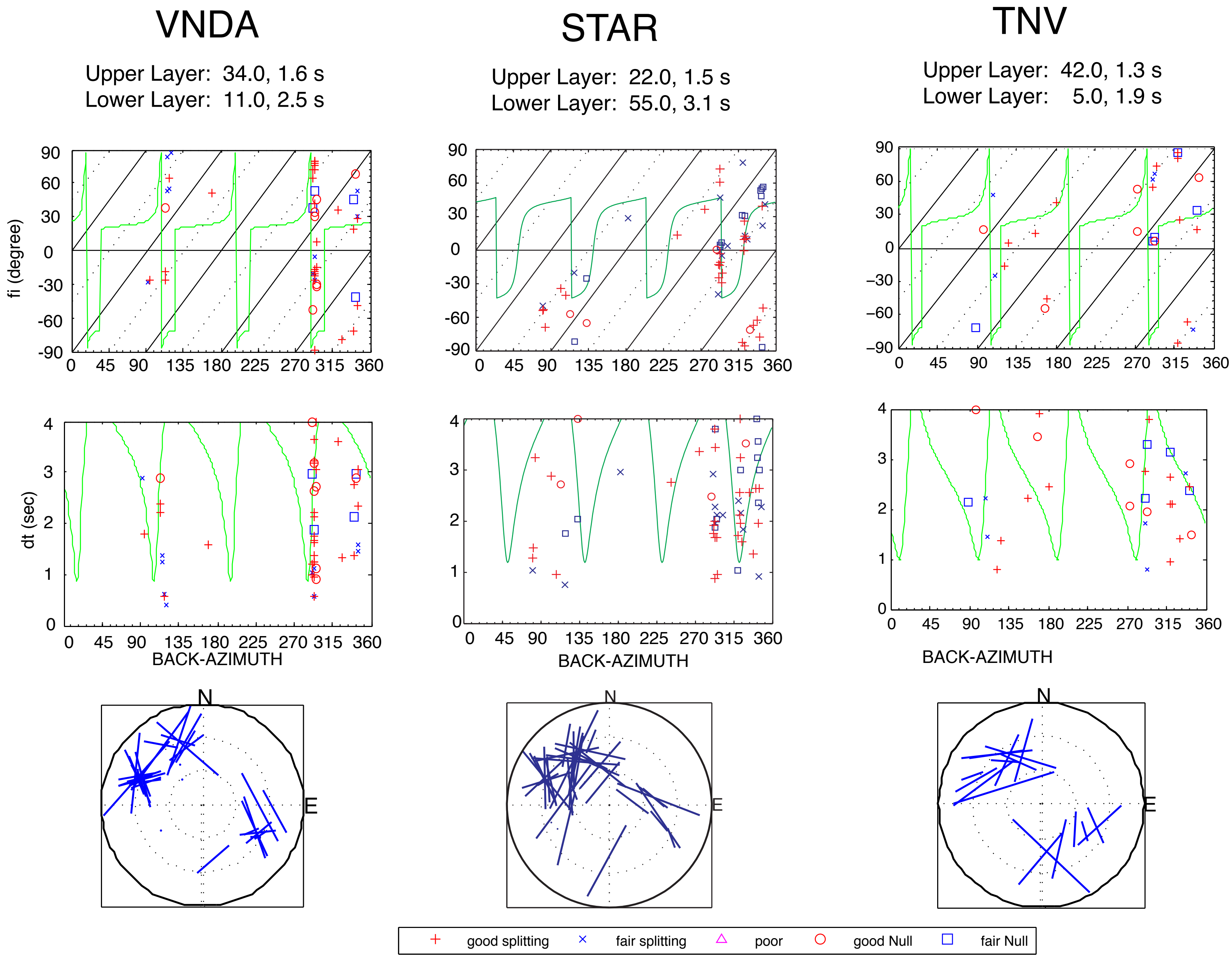
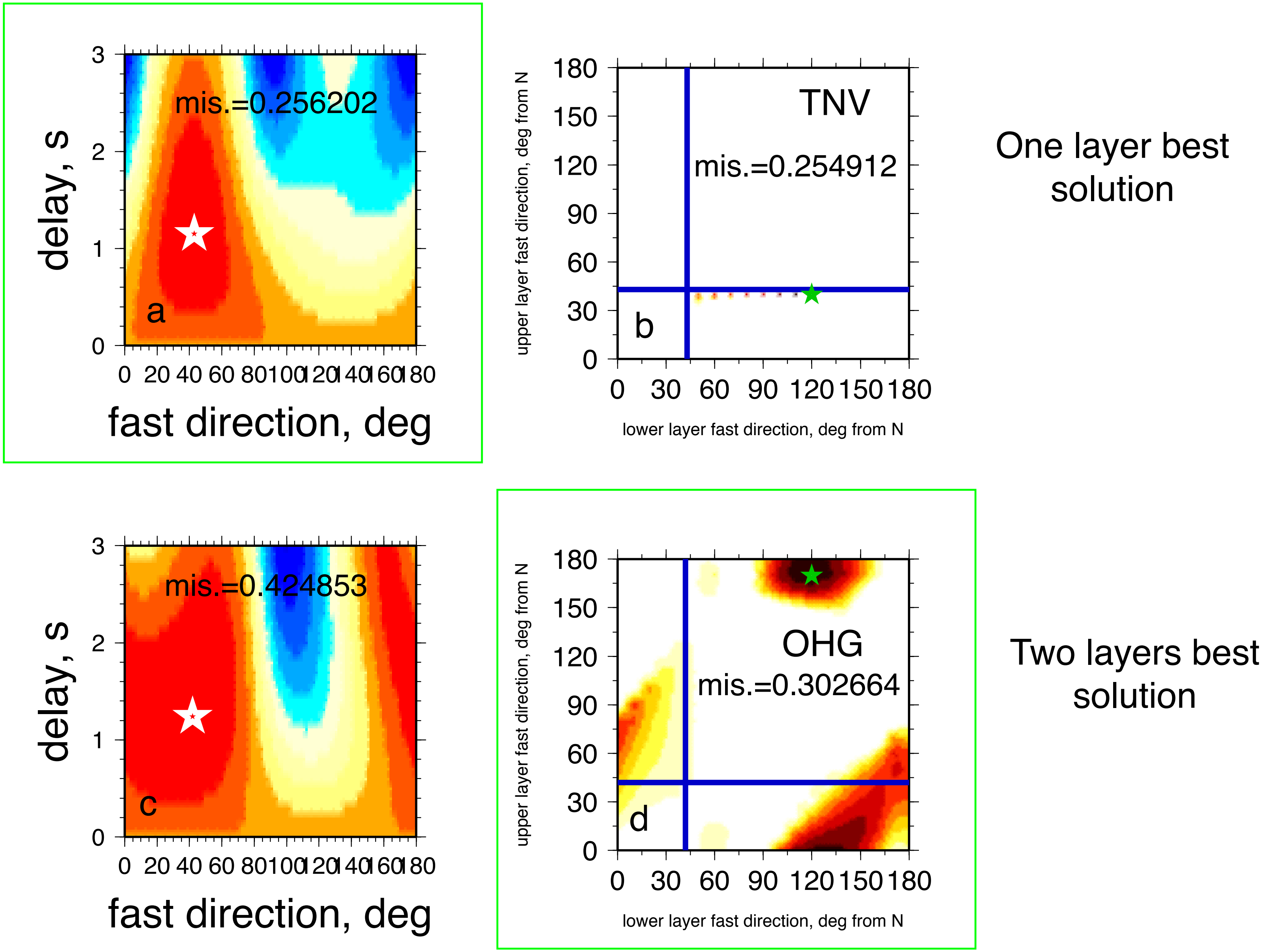
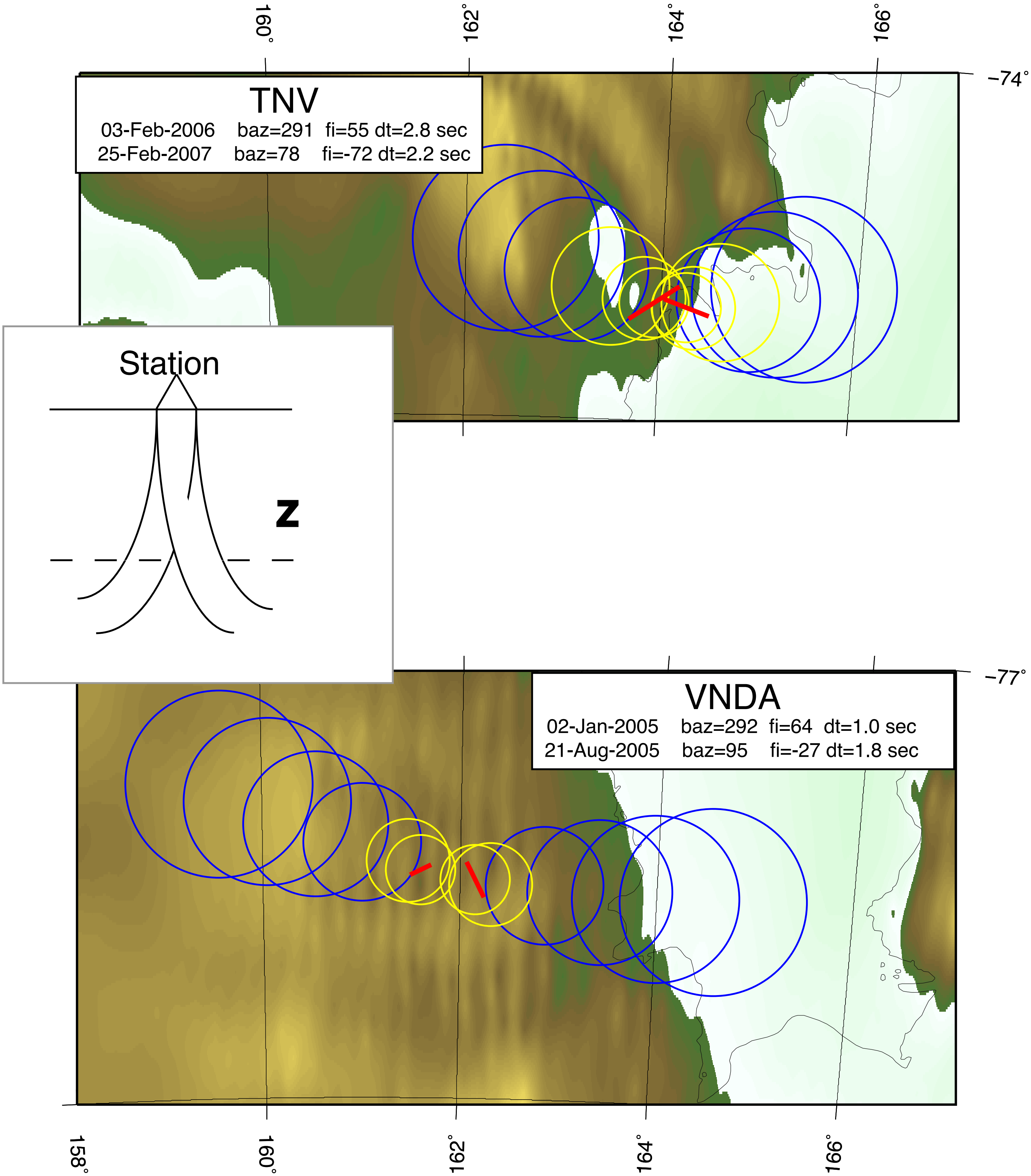

VNDA
Upper Layer: 34.0, 1.6 s
Lower Layer: 11.0, 2.5 s
STAR
Upper Layer: 22.0, 1.5 s
Lower Layer: 55.0, 3.1 s
TNV
Upper Layer: 42.0, 1.3 s
Lower Layer: 5.0, 1.9 s
fi (degree)
dt (sec)
BACK-AZIMUTH
N
E
good splitting
fair splitting
poor
good Null
fair Null

Figure 5



mis.=0.256202
a
delay, s
fast direction, deg
TNV
mis.=0.254912
b
upper layer fast direction, deg from N
lower layer fast direction, deg from N
One layer best solution
mis.=0.424853
c
delay, s
fast direction, deg
OHG
mis.=0.302664
d
upper layer fast direction, deg from N
lower layer fast direction, deg from N
Two layers best solution

FIGURE 6


TNV
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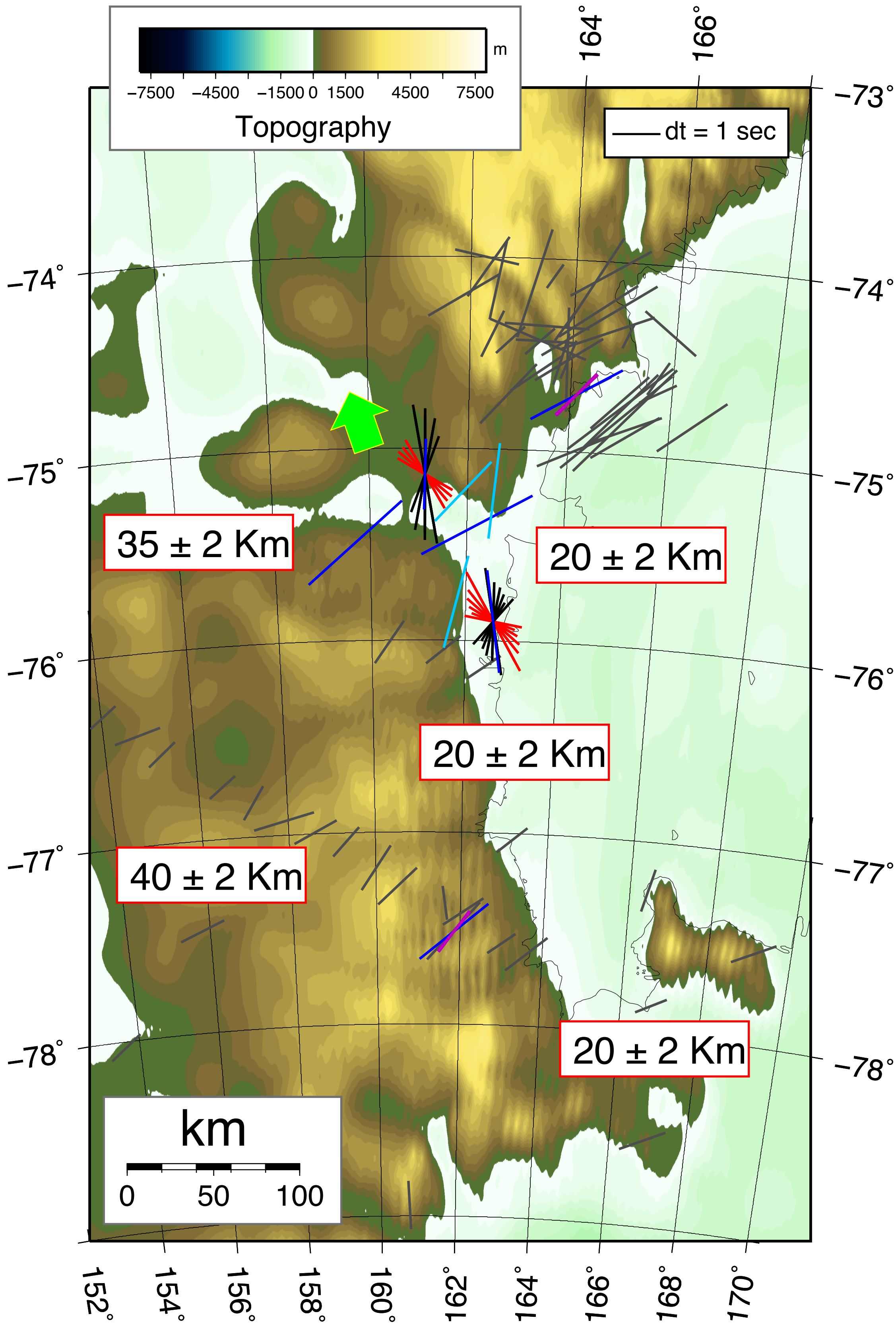
25-Feb-2007 baz=78 fi=-72 dt=2.2 sec
Station
z
VNDA
02-Jan-2005 baz=292 fi=64 dt=1.0 sec
21-Aug-2005 baz=95 fi=-27 dt=1.8 sec
158°
160°
162°
164°
166°
−74°
−77°

Figure 7

Figure 8



m
−7500
−4500
−1500
0
1500
4500
7500
Topography
dt = 1 sec
35 ± 2 Km
20 ± 2 Km
20 ± 2 Km
40 ± 2 Km
20 ± 2 Km
km
0
50
100
164°
166°
−73°
−74°
−74°
−75°
−75°
−76°
−76°
−77°
−77°
−78°
−78°
152°
154°
156°
158°
160°
162°
164°
166°
168°
170°