1 **FAULT KINEMATICS OF THE MAGALLANES-FAGNANO FAULT SYSTEM,**
2 **SOUTHERN CHILE; AN EXAMPLE OF DIFFUSE STRAIN AND SINISTRAL**
3 **TRANSTENSION ALONG A CONTINENTAL TRANSFORM MARGIN**

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11 **Abstract**

12 A system of left-lateral faults that separates the South American and Scotia plates,
13 known as the Magallanes-Fagnano fault system, defines the modern tectonic setting of
14 the southernmost Andes and is superimposed on the Late Cretaceous – Paleogene
15 Patagonian fold-thrust belt. Fault kinematic data and crosscutting relationships from
16 populations of thrust, strike-slip and normal faults from Peninsula Brunswick adjacent to
17 the Magallanes-Fagnano fault system, presented herein, show kinematic and temporal
18 relationships between thrust faults and sets of younger strike-slip and normal faults.
19 Thrust fault kinematics are homogeneous in the study area and record subhorizontal
20 northeast-directed shortening. Strike-slip faults record east—northeast-directed horizontal
21 shortening, west—northwest-directed horizontal extension and form Riedel and P-shear
22 geometries compatible with left-lateral slip on the main splay of the Magallanes-Fagnano
23 fault system. Normal faults record north-south trending extension that is compatible with
24 the strike-slip faults. The study area occurs in a releasing step-over between overlapping
25 segments of the Magallanes-Fagnano fault system, which localized on antecedent sutures
26 between basement terranes with differing geological origin. Results are consistent with
27 regional tectonic models that suggest sinistral shearing and transtension in the
28 southernmost Andes was contemporaneous with the onset of seafloor spreading in the
29 Western Scotia Sea during the Early Miocene.

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1. Introduction

Plate-bounding continental transforms commonly distribute strain along systems of faults that span 10s-1,000s km from the main fault zone (e.g. San Andreas Fault, Bennett et al., 2003; Meade and Hager, 2005; Anatolian Fault, Barka and Kadinsky-Cade, 1988; Şengör et al., 2005; Alpine Fault, Norris et al., 1990; India-Eurasia collision: Morley, 2004; Duval and Clark, 2010). Overlapping strands within the fault system and bends in the trace of the faults typically form regions of localized extension and/or contraction that reflect the sense of shear and geometry of the fault system and may result in the formation of normal or reverse faults that are kinematically compatible with the strike-slip fault system (i.e. releasing or restraining bends or step-overs; e.g. Christie-Blick and Biddle, 1985; McClay and Bonora, 2001). As a result, continental strike-slip margins are commonly characterized by diffuse strain (e.g. Oldow, 2003; Meade and Hager, 2005; Duval and Clark, 2010) that is partitioned among many discrete faults with variable sense-of-slip that altogether accommodate the relative plate motion (e.g. Dokka and Travis, 1990; Prescott et al., 2001; Fuis et al., 2003; Savage et al., 2004; Nemser and Cowan, 2009; McGill et al., 2013). Furthermore, the geometry and location of faults that comprise a transform margin are commonly influenced by antecedent geological and structural architecture of the margin (e.g. rigid blocks, Bennett et al., 2003; Thatcher, 2007; sutures, Şengör et al., 2005; mechanical anisotropy, Crider and Peacock, 2004; Horsman et al., 2008; Nemser and Cowan, 2009). The active Magallanes-Fagnano fault system in Tierra del Fuego (Smalley *et al.*, 2003; 2007; Mendoza *et al.*, 2011) overprints the Cretaceous—Paleogene Patagonian fold-thrust belt (Dalziel and Palmer, 1979; Pelayo & Wiens, 1989; Klepeis, 1994; Klepeis & Austin, 1997; Lodolo *et al.*, 2003; Ghiglione & Ramos, 2005; Menichetti *et al.*, 2008) and is therefore an excellent location to study how strain is distributed within a continental strike-slip plate margin and influenced by the inherited structure and stratigraphy of a fold-thrust belt.

Three major sinistral transform systems accommodate present-day plate motions between the South American, Antarctica and Scotia plates including the Magallanes-Fagnano fault – North Scotia ridge transform, South Scotia Ridge transform and the Shackleton fracture zone (inset of Figure 1; e.g. Barker and Burrell, 1977; Pelayo &

Wiens, 1989; Barker, 2001; Smalley *et al.*, 2003; 2007; Dalziel *et al.*, 2013). The Magallanes-Fagnano fault system is located in southern Argentina and Chile between 52° and 55° S latitude (Pelayo & Wiens, 1989; Figure 1) and accommodates most of the motion between the South American and Scotia plates (Smalley *et al.*, 2003; 2007). Modern geomorphic lineaments and fault scarps of the Magallanes-Fagnano fault system are superimposed on the trend of the Patagonian retroarc fold-thrust belt, a ~700 km long orogenic belt that extends from Tierra del Fuego to the Pacific margin of Chile and records contraction from the Late-Cretaceous to Tertiary Andean Orogeny (e.g. Dalziel and Palmer, 1979; Nelson, 1980; Klepeis, 1994; Ghiglione and Ramos, 2005; Klepeis *et al.*, 2010; Fosdick *et al.*, 2011; Betka *et al.*, 2015).

The tectonic origin and timing of the onset of sinistral deformation along the Magallanes-Fagnano fault system has been the subject of some debate for several decades (e.g. Cunningham, 1993; Cunningham *et al.*, 1995; Diraison *et al.*, 2000; Kraemer, 2003; Ghiglione & Cristallini, 2007). Some interpretations suggest that sinistral deformation occurred since the Late Cretaceous and that the Patagonian fold-thrust belt is product of Cretaceous-Tertiary wrench tectonics that occurred during and since the Andean Orogeny (Cunningham 1993; Cunningham, 1995; Menichetti *et al.*, 2008). Other authors interpret the development of the thrust belt and onset of strike-slip deformation as having occurred as two separate tectonic events and conclude that strike-slip deformation has overprinted the thrust belt since the Oligocene (Klepeis, 1994; Klepeis & Austin, 1997; Lodolo *et al.*, 2003; Ghiglione & Ramos, 2005). Most studies of the Magallanes-Fagnano fault system focus on a region of Tierra del Fuego near Lago Fagnano or the Beagle Channel where the fault strands are well exposed (Figure 1), however, the spatial extent of strike-slip related deformation and field relationships with thrust related deformation in the Patagonian fold-thrust belt beyond Tierra del Fuego are not well understood (e.g. Winslow, 1982; Cunningham, 1993; Diraison *et al.*, 1997; 2000; Lodolo *et al.*, 2003).

This paper presents the results of a kinematic analysis of a population (n = 235) of thrust, strike-slip and normal faults that occur within a previously unmapped ~100 km² region of the Patagonian fold-thrust belt located on Peninsula Brunswick and the southern shore of Isla Riesco in southern Chile (Figure 1, 2). The goals of this study were to 1) determine the spatial extent of strike-slip deformation along-strike to the northwest from

where it is well described on Tierra del Fuego, 2) test for kinematic compatibility between populations of thrust, strike-slip and normal faults in the study area and, 3) document field cross-cutting relationships between thrust, strike-slip and normal faults. The results document the occurrence of coeval sets of strike-slip and normal faults that postdate the thrust-belt and record sinistral transtension within a left-lateral, left-stepping segment of the Magallanes-Fagnano fault system. The results are discussed in the context of a transition from contraction to left-lateral shear that probably occurred in the early Miocene and define separate tectonic events.

2. Tectonic setting and geologic background

2.1 MAGALLANES-FAGNANO FAULT SYSTEM

The Magallanes-Fagnano fault system transects Isla Grande of Tierra del Fuego and occupies the northwest-trending segment of the Estrecho de Magallanes near the Pacific margin (Figure 1). Toward the northwest, the Magallanes-Fagnano fault system terminates at a trench-transform triple junction between the Antarctic, South American and Scotia plates. East of Tierra del Fuego, the Magallanes-Fagnano fault system joins the North Scotia Ridge, a sinistral transform boundary that extends from Tierra del Fuego >1700 km east toward South Georgia island and defines the northern boundary of the Scotia Sea plate (inset of Figure 1; Pelayo & Wiens, 1989). On Tierra del Fuego, GPS data indicate that the present-day slip rate along the Magallanes-Fagnano transform is 6.6 ± 1.3 mm/yr and that an additional 1-2 mm/yr of sinistral slip is accommodated by diffuse deformation in Tierra del Fuego and southern Patagonia (Smalley *et al.*, 2003). Similarly, Mendoza *et al.* (2011) measured an average horizontal velocity (sinistral motion) of 4.4 ± 0.6 mm/yr over a 30 km wide zone centered on the main trace of the Magallanes-Fagnano fault system. Relative plate motions are consistent with earthquake focal mechanism solutions from two events that occurred along the Magallanes-Fagnano fault segment on Tierra del Fuego (Smalley *et al.*, 2007) and offshore toward the east (Pelayo & Wiens, 1989) that both indicate nearly pure strike-slip sinistral motion.

In Tierra del Fuego and the Magallanes region of Chile, the Magallanes-Fagnano fault system consists of an array of steeply-dipping, sinistral transform faults that strike west near Tierra del Fuego and northwest near the Pacific margin of Chile (Figure 1). Individual fault strands are arranged in an en-echelon arrays that contain both right- (restraining step-over) and left- (releasing step-over) stepping segments. Asymmetric, normal fault bounded basins (10s of km² scale) are commonly associated with releasing step-overs and oblique contractile folds are documented within restraining step-overs (Figure 1, Winslow, 1982; Klepeis & Austin, 1997; Lodolo *et al.*, 2003; Menichetti *et al.*, 2008). Lago Fagnano and Seno Almirantazgo (Figure 1) form prominent west trending lineaments that occupy oblique-normal fault bounded basins within a left-stepping segment of the fault zone (Klepeis, 1994; Klepeis & Austin, 1997; Lodolo *et al.*, 2003; Menichetti *et al.*, 2008; Esteben *et al.*, 2014).

Fuenzalida (1974) conducted the first detailed field-based structural analysis of the Magallanes-Fagnano fault system. Later, kinematic analyses by Klepeis (1994) demonstrated that the fault zone is characterized by dominantly sinistral strike-slip motion with a lesser component of normal-slip. He reported 20-25 km of sinistral separation and as much as 3 km of throw based on an offset thrust contact exposed near the western end of Lago Fagnano. Lodolo *et al.* (2003) postulated that the Magallanes-Fagnano fault system accommodated as much as 40 km of sinistral offset by extrapolating a GPS-based slip rate (~0.5 mm/yr after Del Cogliano *et al.*, 2000) back in time to the cessation of seafloor spreading in the Scotia Sea at 8 Ma (after Barker and Burrell, 1977). Kinematic analyses of brittle faults along the Magallanes-Fagnano fault segment near Lago Fagnano reported by Menichetti *et al.* (2008) indicate a dominant population of sinistral strike-slip faults and a smaller population of normal faults that is also consistent with the kinematic data of Klepeis (1994) and Klepeis and Austin (1997).

2.2 TIMING OF STRIKE-SLIP DEFORMATION

Field-based constraints on the age of the onset of strike-slip deformation are limited. Klepeis (1994) postulated that sinistral strike-slip deformation on Tierra del Fuego occurred after 60 Ma and dominantly since 30 Ma based on field observations indicating that strike-slip structures consistently crosscut Late Cretaceous contractional

structures. In support of field observations, reflection seismic data across the Magallanes-Fagnano transform fault, collected along the north trending segment of the Magallanes Strait, demonstrates that the main strand of the Magallanes-Fagnano fault overprints Cretaceous contractional structures (Klepeis and Austin, 1997) and is interpreted by the authors to be a result of the Oligocene onset of seafloor spreading in the Scotia Sea (*i.e.* ~30 Ma; Barker and Burrell, 1977). In contrast, Lodolo *et al.* (2003; 2006) proposed a late Miocene (<9.5-6 Ma) age for the onset of sinistral translation along the Magallanes-Fagnano fault system. These authors postulate a causal response between the cessation of sea floor spreading in the western Scotia Sea (Lodolo *et al.*, 2006) and the onset of strike-slip deformation in Tierra del Fuego.

A tectonic model proposed by Cunningham (1993) suggests that the Andean Orogeny in Tierra del Fuego was caused by sinistral transpression since 120 Ma as South America moved westward relative to the Antarctic Peninsula. This model is in part supported by a plate reconstruction that allows up to 1320 km of left-lateral strike-slip displacement has occurred between southern South America and the Antarctic Peninsula since the relative westward rate of motion of southern South America increased *c.* 84 Ma. The model suggests that ~900 km of the motion occurred after 50 Ma (Cunningham *et al.*, 1995). Although the absolute timing of the onset of strike-slip deformation in the southern Andes remains under debate, most authors agree that it is probably spatially variable and occurred mostly during the Cenozoic (see discussions by Klepeis 1994; Cunningham *et al.*, 1995; Lodolo *et al.*, 2003; Menichetti *et al.*, 2008; and review by Dalziel *et al.*, 2013).

2.3 GEOLOGY OF THE STUDY AREA ON PENINSULA BRUNSWICK

Peninsula Brunswick is located in the Magallanes region of Chile, to the southwest, it is bound by the Magallanes-Fagnano fault system (Figure 1, 2). Prominent southeast-trending lineaments that transect Peninsula Brunswick largely reflect the structural trend of the Late-Cretaceous—Paleogene Patagonian fold-thrust belt, which imbricates all of the units in the study area (Figure 1, 2). The Patagonian fold-thrust belt developed in two main stages of Cretaceous—Paleocene shortening, the first generation of structures

reflect largely Late Cretaceous thin-skinned deformation that resulted in a thrust wedge and propagation of the thrust front into the nascent Magallanes foreland basin (Alvarez-Marrón *et al.*, 1993; Klepeis, 1994a; Ghiglione and Ramos, 2005; Mpodozis & Rojas, 2006; Rojas & Mpodozis, 2006; Ghiglione *et al.*, 2010; Klepeis *et al.*, 2010; Fosdick *et al.*, 2011; Betka *et al.*, 2015). First generation contractional structures are commonly cut by a second generation of high-angle reverse faults that reflect Maastrichtian—Eocene basement uplift and inversion of Jurassic normal faults (faults with white-filled teeth in Figure 2; Winslow, 1981; Klepeis, 1994a; Mpodozis & Rojas, 2006; Rojas & Mpodozis, 2006; Klepeis *et al.*, 2010; Fosdick *et al.*, 2011; Betka *et al.*, 2015).

The geology of Peninsula Brunswick consists of four major lithotectonic units, the Cordillera Darwin metamorphic complex, Rocas Verdes terrane, Patagonian Batholith and Magallanes foreland basin (described below, Figure 2). The Cordillera Darwin metamorphic complex (Darwin, 1846; Kranck, 1932; Nelson *et al.*, 1980; Kohn *et al.*, 1993; 1995; Cunningham *et al.*, 1995; Hervé *et al.*, 2003, 2010; Klepeis *et al.*, 2010; Maloney *et al.*, 2011) comprises the local ‘basement’ and is the oldest unit in the study area. The Cordillera Darwin metamorphic complex occurs in a southeast-trending outcrop belt that is uplifted in the hanging wall of a southeast-striking basement-involved reverse fault (Figure 2). On Peninsula Brunswick it is a quartz-chlorite schist that reflects Cretaceous greenschist facies metamorphism of Upper Paleozoic passive margin sediments (Hervé *et al.*, 2010; Betka, 2010).

Overlying and imbricated with the Cordillera Darwin metamorphic complex are a suite of Jurassic – Early Cretaceous volcanic, volcanoclastic and marine mudstones that define the Rocas Verdes Basin terrane and were deposited in a marginal basin setting during the rifting of Gondwana (Dalziel *et al.*, 1974; Bruhn *et al.*, 1978; Dalziel, 1981; Pankhurst *et al.*, 2000). A suite of basalt, gabbro, mudstone, chert and slate crop out in the northwestern part of the study area (Figure 2, Betka, 2013). Silicic volcanic and volcanoclastic rocks, known as the Tobifera Formation (Dalziel and Cortés, 1972; Natland, 1974; Gust *et al.*, 1985; Hanson and Wilson, 1991; Pankhurst *et al.*, 2003), form a southeast-trending outcrop belt that is bound by southeast-striking thrust faults (Figure 2; Betka, 2013). Both suites of mafic and silicic volcanic rocks are interpreted to reflect bimodal submarine volcanism that occurred during the Jurassic opening of the Rocas

Verdes basin and ultimately formed the floor of the basin (Dalziel, *et al.*, 1974; Dalziel, 1981; Stern & De Wit, 2003; Calderón *et al.*, 2007). Conformably overlying and imbricated with the volcanic floor of the basin is a thick (>1000 m) succession of marine mudstones and distal turbidite deposits, known as the Zapata and Canal Bertrand Formations, that reflect Late Jurassic – Early Cretaceous sedimentation into the Rocas Verdes Basin (Fildani *et al.*, 2003; Fildani & Hessler, 2005; Mpodozis *et al.*, 2007; McAtamney *et al.*, 2011). The Patagonian Batholith crops out southwest (outboard) of the Rocas Verdes terrane (Figure 2). The batholith resulted from Jurassic—Neogene subduction-related magmatism along the western margin of Gondwana and later South America and is comprised of a suite of Late Jurassic bimodal leucogranite and gabbro as well as Cretaceous to Neogene granitoids (Suárez and Pettigrew, 1976; Hervé *et al.*, 1984; Bruce *et al.*, 1991; Fildani and Hessler, 2005; Hervé *et al.*, 2007).

Tectonic loading associated with the closure and imbrication of the Rocas Verdes Basin during the Late Cretaceous Andean orogeny ultimately resulted in the formation of the Patagonian fold-thrust belt and a flexural basin known as the Magallanes foreland basin (Katz, 1963; Scott, 1966; Natland *et al.*, 1974; Winn and Dott, 1979; Biddle *et al.*, 1986; Wilson, 1991; Fildani *et al.*, 2003; Fildani & Hessler, 2005; Hubbard *et al.*, 2008; Fildani *et al.*, 2009; Barbeau *et al.*, 2009; Gombosi *et al.*, 2009; Zahid and Barbeau, 2010; Romans *et al.*, 2010; Romans *et al.*, 2011; Bernhardt *et al.*, 2011). Turonian—Coniacian turbidite deposits, called the Latorre Formation, reflect syntectonic sedimentation into the Magallanes basin and conformably overlie and are imbricated by thrust faults with the Zapata and Canal Bertrand formations of the Rocas Verdes terrane (Figure 2; Mpodozis *et al.*, 2007; McAtamney *et al.*, 2011). Continued Late Cretaceous sedimentation into the Magallanes basin resulted in the deposition of submarine fan channel-fill conglomerates and turbidite deposits (Escarpada Formation, late Coniacian—Campanian; Mpodozis *et al.*, 2007; McAtamney *et al.*, 2011) and slope, shelf-edge (Fuentes Formation, Campanian—Maastrichtian; Mpodozis *et al.*, 2007) and nearshore estuarine deposits (Rocallosa Formation, Maastrichtian—Danian; Mpodozis *et al.*, 2007). In the study area, Late Cretaceous rocks of the Magallanes foreland basin form southeast-trending outcrop belts that are bound and tectonically imbricated by southeast-striking thrust faults of the Patagonian fold-thrust belt (Figure 2; Betka, 2013).

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245 **3. Methodology**

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247 Fault-slip data including the attitudes of fault planes and striae as well as sense-
248 of-slip was collected from faults everywhere they were observed in the field. Sense-of-
249 slip was determined using observed offsets and common fault-slip indicators including
250 fault surface asperities ('steps'), secondary fractures such as Riedel-shears as well as
251 tensile and/or sigmoidal vein orientations (*e.g.* Petit, 1987). Where possible, multiple
252 sense-of-slip indicators were noted for the majority of faults measured. The quality of
253 shear-sense indicators were ranked on a three-point scale. For example, a fault with
254 measurable offset was given an 'A' rank, one with clearly defined kinematic indicators
255 such as Riedel-shears but no discernable offset layers was given a 'B' rank and a fault
256 with ambiguous kinematic indicators was ranked 'C'. The three-point scheme allowed a
257 simple classification of the quality of the data that was considered (but not weighted)
258 when interpreting the dataset.

259 Kinematic analyses of the fault-slip data were conducted using the methods of
260 Marrett and Allmendinger (1990), which facilitates a graphical comparison of the
261 distribution and orientations of average incremental strain axes among populations of
262 kinematically scale-invariant faults. Shortening and extension axes (kinematic axes) were
263 calculated for each fault by bisecting the angle between the pole to the fault plane and the
264 slip lineation and thus always lie within the movement plane (defined by the pole to fault
265 and slip-lineation, Aleksandrowski, 1985) at 45° to those features. Directional maxima
266 for a population of shortening and extension axes representing a set of faults were
267 calculated using the linked Bingham distribution statistics function of *FaultKin* and
268 considered to reflect the average incremental strain axes of the population (Marrett and
269 Almendinger, 1990). Fault-slip data were weighted equally and assumed to be scale-
270 invariant, the latter assumption is supported by both theoretical (*e.g.* Turcotte, 1986) and
271 natural (*e.g.* Marrett & Allmendinger, 1992) examples of fault populations. Fault plane
272 solutions were constructed from the linked Bingham axes and plotted to illustrate the
273 average kinematics from a population of faults.

To test for spatial homogeneity of faulting, the scale-invariance of fault populations and the kinematic compatibility of fault-slip data in the study area, stereograms of faults and striae as well as kinematic axes (incremental strain axes) and fault plane solutions from different field locations were compared statistically. Fault populations with subparallel kinematic axes and/or slip directions were considered to be kinematically compatible and scale-invariant. Subsets of fault populations with anomalous kinematic axes and/or slip directions were considered separately. To delineate subsets with statistically distinct fault kinematics, shortening and extension axes were contoured using the Kamb method. For large subsets of faults ($n > \sim 20$) 95% confidence intervals were calculated for Bingham axes (directional maxima for populations of shortening and extension axes) and plotted as small circles using *FaultKin* and *Stereonet* software programs (Marrett and Allmendinger, 1990; Allmendinger et al., 2013; Cardozo and Allmendinger, 2013). Both brittle and semi-brittle fault zones are considered in this study. Because this study only considers fault kinematics and does not address the mechanical behavior of the faults, it is considered reasonable to compare kinematic axes from both brittle and semi-brittle fault zones and discuss them in the context of understanding the orientation and distribution of average incremental strain axes for fault populations. This method is advantageous because it is possible to assess the kinematic compatibility of a large population of faults by graphical comparison, however, it does not consider the mechanical properties of the faults.

4. Structure of Peninsula Brunswick near the Estrecho de Magallanes

In this section we present new field data and a new geologic map and cross section of the Patagonian fold-thrust belt. Shoreline exposures along a 30-km transect from Cabo Froward toward the northeast preserve the structure of the Magallanes foreland basin in the southeastern most part of the study area (Transect A-A'; Figure 2, 3, 4). Here, structures of the fold-thrust belt of overprinted by strike-slip faults that are inferred to be part of the Magallanes-Fagnano fault system (discussed below; c.f. Winslow, 1982; Klepeis & Austin, 1997; Lodolo et al., 2003; Menichetti *et al.*, 2008; Betka, 2013). This area, thus, is an important locality to study the kinematic relationship

304 between thrusting and strike-slip deformation. See Betka et al., 2015 for a detailed
305 description of the geology shown in Figures 6 and 7.

306 Near Cabo Froward at the southwestern end of transect A-A', the Tobífera
307 Formation crops out along the Estrecho de Magallanes and can be correlated using
308 satellite imagery with previously mapped outcrops to the northwest (Figure 2, 3; see
309 Betka, 2013; Betka et al., 2015). Near Cabo Froward, the top of the Tobífera Formation is
310 exposed and sheared. A schistose white mica and quartz foliation (S_I) dips north and
311 contains a well-defined, recrystallized, quartz lineation that plunges toward the north (L_I ,
312 Figure 4a, b). On surfaces oriented perpendicular to S_I and parallel to L_I , rigid, feldspar
313 porphyroclasts with asymmetric recrystallized quartz tails and C' shear bands that
314 truncate and displace S_I indicate top-north sense of shear.

315 Above the contact at Cabo Froward, the Zapata-Canal Bertrand Formation crops
316 out and is pervasively deformed. Bedding (S_0) of the Zapata-Canal Bertrand Formation is
317 folded into tight, northeast-vergent overturned folds with northwest-plunging fold axes
318 (F_I) and west-southwest-dipping axial planes (S_I). A prominent cleavage-bedding
319 intersection lineation (S_I) is exposed on bedding surfaces and is parallel to F_I fold axes
320 (Figure 4c, d). At Cabo Froward, F_I folds in the Zapata-Canal Bertrand Formation are
321 detached from the underlying Tobífera Formation which is not folded. The top-to-the-
322 north sense of shear at the contact between the two formations is compatible with the
323 vergence of the overturned folds in the overlying Zapata-Canal Bertrand Formation and
324 altogether, these structures form part of the Canal Bertrand décollement zone defined by
325 Betka et al. (2015).

326 A basement-involved, southwest-dipping reverse fault is inferred and mapped in
327 the valley north of Cabo Froward to explain the juxtaposition of stratigraphic levels
328 between exposures of the Tobífera-Zapata-Canal Bertrand contact in the hanging wall
329 and the Zapata-Canal Bertrand-Latorre contact in the footwall (Figure 3, 4a). Using
330 satellite imagery, this fault is correlated with a second-generation thrust that uplifts the
331 Tobífera Formation where it crops out in Estuarios Silva Palma and Wickham to the
332 northwest (Figure 2)(Betka et al., 2015). A minor southeast-dipping normal fault cuts the
333 reverse fault and strikes northeast along the valley between Cabo Froward and Peninsula
334 Brunswick (Figure 3, 4a). To the north of these faults, the upper part of the Zapata-Canal

Bertrand Formation is exposed and is not deformed. Bedding (S_0) dips steeply toward the north. The contact between the Zapata-Canal Bertrand Formation and overlying Latorre Formation is exposed near site 10217 (Figure 3) where it is conformable and dips north. Above the contact the full thickness of the Latorre Formation (~1200 m) is intermittently exposed. The Escarpada Formation conformably overlies the Latorre Formation and also dips to the north (Figure 3, 4).

Approximately 1 km northeast of site 10217, a back thrust juxtaposes the base of the Latorre Formation against the Escarpada Formation (Figure 3, 4). In the hanging wall of the back thrust, bedding (S_0) is folded by a regional syncline. Mesoscale (~5 m wavelengths) second order folds have axes that trend north-northwest and steeply southwest-dipping or upright axial planar cleavages (S_1). Bedding-cleavage intersection lineations occur on bedding surfaces and trend north-northwest (Figure 4e, f). The northern limb of the syncline is truncated by a southwest-dipping thrust fault that uplifts the Latorre Formation in the hanging wall above the Escarpada Formation in the footwall. On the basis of the stratigraphic separation across the fault, the thrust is inferred to be detached at the base of the Zapata-Canal Bertrand Formation, and it forms a pop-up structure with the back thrust exposed to the south (Figure 4a).

To the north of the pop-up structure, the Escarpada Formation is imbricated by a southwest-dipping thrust fault that also is inferred to be detached at the base of the Zapata-Canal Bertrand Formation on the basis of geometric constraints from stratigraphic thicknesses (Figure 4a). In the hanging wall, bedding is folded into a regional syncline-anticline pair. Second order folds in the core of the syncline are overturned-to-the-northeast and have northwest-southeast-trending horizontal fold axes. In the footwall north of Punta Brigida (Figure 3), regional F_1 folds are upright and tighter than those in the hanging wall. Second-order F_1 folds display a subvertical axial planar cleavages (S_1 , Figure 4a, g-h). Near site 10338 (Figure 3), bedding dips vertically and is cut by a 2 m wide sinistral strike-slip fault zone that strikes northwest subparallel to bedding (Figure 3, 4a). The amount of offset is unknown, however a conservation of stratigraphic thicknesses require at least 1 km of throw across the fault indicating a reverse-sinistral sense-of-motion (Figure 4a).

On the south shore of Bahía del Indio, the Escarpada Formation crops out and is subvertical. Here, clustered sets of conjugate strike-slip faults cut bedding and indicate dominantly sinistral slip. On the north shore 1.5 km toward the northeast, strata of the Fuentes/Rocallosa Formation dip shallowly to the southwest. A high-angle basement-involved reverse fault is inferred to explain the stratigraphic separation across the bay. This fault probably correlates with similar structures exposed near Seno Otway, ~100 km to the northeast (Figure 2) (see Betka et al., 2015). The fault also is inferred to have a left-lateral component of motion on the basis of the clustered sets of conjugate faults on the south shore of Bahia del Indio (discussed below).

Toward the north in the footwall of the basement-involved fault, the Fuentes/Rocallosa Formation is folded by a series of three tight upright folds with ~2 km wavelengths (F_1). A vertical spaced cleavage is axial planar to the folds (S_1). Fold axes and cleavage-bedding intersection lineations plunge shallowly toward the northwest (Figure 4i-j). Several sets of conjugate strike-slip faults cluster on the limb of the fold near Bahía del Aguila and show dominantly sinistral-slip. A steeply-dipping, bedding parallel, left-lateral strike slip fault is mapped along the north shore of Bahía del Aguila where conjugate fault sets are densely clustered (Figure 3, 4a). Tight upright folds and strike-slip deformation preserved on the northern end of transect A-A' post-date the fold-thrust belt and probably reflect Neogene strike-slip tectonics (discussed below).

5. Fault kinematic data

A population (n=235) of fault kinematic data was collected from three study areas located between Seno Otway and the Estrecho de Magallanes. To describe the spatial distribution of different types of deformation (e.g. thrust vs. strike-slip faults), the data are organized into separate populations of thrust, strike-slip and normal faults and are discussed according to location (see Figure 2): 1) Cabo Forward and the Estrecho de Magallanes toward the southeast, 2) Estuario Silva Palma, Seno Cordes and Bahía Fortesque near central Peninsula Brunswick and 3) Canal Jeronimo, Seno Otway and

Estuario Wickham to the northwest. Refer to Betka et al. (2015) for a detailed description of the structure of the Patagonian fold-thrust belt in the study area.

5.1 THRUST FAULTS

Southeastern localities: Eleven thrust faults were measured near Cabo Froward from exposures within the Zapata-Canal Bertrand Formation and Late Cretaceous foreland basin strata (Figure 5). At Cabo Froward, a set of four out-of-syncline thrust faults truncate overturned F_1 tight folds within the Zapata-Canal Bertrand Formation (Figure 5a). The thrust faults dip gently toward the west and contain down-dip calcite slip lineations and tool marks (Figure 5b). A set of tensile calcite veins that formed adjacent to the thrust faults trends east and helps to confirm a top-to-the-northeast thrust sense of motion (Figure 5c). Northward along the Estrecho de Magallanes, sets of both synthetic and antithetic minor thrust faults imbricate the Latorre and Escarpada Formations and dip moderately toward the northeast and southwest. Slip lineations defined by calcite fibers and mechanical grooves trend down-dip (Figure 5d-e).

Central localities: A population of 16 thrust faults from Estuario Silva Palma and 11 thrust-sense ductile shear bands from the Cordillera Darwin Metamorphic Complex schist exposed in Bahía Fortesque and Seno Cordes were measured. Near Estuario Silva Palma, the second generation Tobífera thrust is well exposed at sea level in three locations (Figure 6a). Everywhere this thrust dips shallowly to the southwest and contains down-dip quartz stretching lineations (Figure 6a). In the footwall, out of syncline thrusts that thicken the Zapata-Canal Bertrand Formation dip dominantly toward the southwest and contain down-dip to oblique south-southwest plunging calcite slip lineations (Figure 6b). In Seno Cordes toward the south, a ductile shear zone is exposed at the base of the Tobífera Formation where it dips steeply to the west-southwest and contains down-dip quartz stretching lineations (Figure 6c). In Bahía Fortesque, thrust-sense shear bands that indicate top-northeast sense-of-shear dip shallowly to the southwest and contain down-dip to oblique southwest to south-southwest plunging quartz stretching lineations (Figure 6d).

Northwestern localities: Fault kinematic data were collected from 29 thrust faults exposed along the shores of Canal Jeronimo and Seno Otway (Figure 7). Near Canal

Jeronimo, first generation thrust faults that imbricate the Tobífera Formation and a thrust that imbricates rocks of the Rocas Verdes Basin terrane (Figure 7a-c) all display moderately southwest-dipping fault surfaces with down-dip, southwest-plunging or oblique south-southwest plunging slip lineations. Minor fault planes associated with second-generation thrusts near Canal Jeronimo dip steeply toward the southwest and have down-dip slip lineations. Kinematic axes of the second generation thrusts (Figure 7d, e) are subparallel to those of first generation thrusts (Figures 7a-c). Near Seno Otway, eight first-generation minor thrust faults are located in the footwalls of map scale thrusts that imbricate Late Cretaceous foreland basin strata. The minor faults form both synthetic and antithetic fault sets (Figure 7f-g). Synthetic faults dip shallowly south-southwest and southwest and contain down-dip to obliquely plunging striae. Antithetic faults dip steeply toward the east-northeast and contain steeply north plunging striae (Figures 7f-g).

Near Estuario Wickham (Figure 8), minor thrust faults occur in the hanging wall of the second-generation thrust located at the base of the Tobífera Formation. The fault planes dip shallowly to the west-southwest and contain down-dip striae (Figure 8a). In the hanging wall of the Tobífera thrust, first-generation thrust-sense shear bands that thicken the Cordillera Darwin Metamorphic Complex are axial planar to F_1 folds (see Betka et al., 2015), dip steeply toward the southwest, and contain down-dip quartz and mica mineral lineations (Figure 8b-c). Second-generation reverse faults that juxtapose the Cordillera Darwin Metamorphic Complex above the Tobífera Formation dip steeply toward the west and contain down-dip quartz stretching lineations (Figure 8d). In the footwall of the Tobífera thrust, minor thrusts that shear the limbs of first-generation overturned folds within the Zapata-Canal Bertrand Formation (see Betka et al., 2015), dip shallowly toward the southwest and contain down-dip white mica lineations and tool marks (Figure 8e). A small population of minor back thrusts ($n=5$) occur within the Latorre Formation. The back thrusts dip dominantly toward the north-northeast and also contain down-dip slip lineations (Figure 8f-g). One antithetic thrust dips shallowly toward the south-southwest (Figures 8f-g).

5.2 STRIKE-SLIP FAULTS

Southeastern localities: Along the Estrecho de Magallanes for 30 km northeast of Cabo Froward (Figure 9), folds and thrusts of the Cretaceous foreland thrust belt are overprinted by a substantial ($n = 105$) population of brittle strike-slip faults. Calcite-filled tensile (*i.e.* mode-I fractures) and sigmoidal veins also occur and are commonly associated with the faults. The veins dominantly strike east to northeast and are generally parallel to shortening axes associated with the strike-slip faults, indicating that veining and faulting were probably contemporaneous and lending credence to kinematic interpretations of the faults that are based on fault surface asperities and/or secondary fractures (Figures 9, 10).

Near Cabo Froward, several left-lateral strike-slip faults strike west and crosscut F_1 folds and thrusts that thicken the Zapata-Canal Bertrand Formation (Figure 9a, 10a). At this locality, one right-lateral fault strikes northeast in a conjugate-style orientation to the left-lateral set (Figure 9a). Between Cabo Froward and Bahía Rosa (Figure 9), a set of both right-lateral and left-lateral minor strike-slip faults crosscut tilted Late Cretaceous strata of the Latorre and Escarpada Formations (Figure 9b, 10b). Left-lateral faults occupy two common orientations, one set strikes west-northwest and the second set strikes north-northwest (Figure 9b). All right-lateral faults strike northeast (Figure 9b). Less than 5 km northeast of Bahía Rosa (Figure 9), F_1 folds that thicken the Latorre Formation are crosscut by a set of right- and left-lateral faults that occupy similar orientations to those toward the southwest. Left-lateral faults strike east-northeast and northwest, and right-lateral faults strike northeast (Figure 9c). Near Punta Glasgot and Punta Brigida (Figure 9d, e), a small population of strike slip faults crosscuts F_1 folds within the Escarpada Formation. At this locality, left-lateral faults strike east-northeast and northwest, and right-lateral faults strike north-northeast. North of Punta Brigida near Bahía del Indio and Bahía del Aguila, strike-slip deformation intensifies. Between Punta Brigida and Bahía del Indio, a large set ($n=49$) of both left- and right-lateral faults crosscut steeply dipping strata of the Escarpada Formation (Figure 9f, g, 10c). At this location, left-lateral faults strike dominantly east-northeast. Near site 10338 (Figure 9), a ~5 m wide intensely fractured zone that contains cataclasite defines a northwest-striking left-lateral fault zone (Figure 10d). All right-lateral faults in this population are north- or

northeast-striking (Figure 9f). Near Bahía del Aguila, both right- and left-lateral fault sets crosscut folded Maastrichtian strata of the Fuentes-Rocallosa Formations (Figure 9g, 10e, f). Here, all right-lateral faults strike north to northeast, and all left-lateral faults strike east-northeast. One left-lateral fault strikes northwest (Figure 9g).

Central and northwestern localities: Strike-slip faults are not common in Estuario Silva Palma (n=2), however, where they occur they crosscut F_1 folds within the Zapata-Canal Bertrand Formation. A right-lateral fault strikes northeast a left-lateral fault strikes northwest (Figure 11a). A small population (n=21) of strike-slip faults also crop out near Seno Otway and Estuario Wickham (Figure 12). In Seno Condor at the southwest corner of Canal Jeronimo, five strike-slip faults are exposed. Four of the faults strike northeast and are right-lateral, and one fault strikes west-northwest and is left-lateral. Striae on all of the fault planes are subhorizontal (Figure 12a). Evidence for strike-slip deformation is absent along Canal Jeronimo between Seno Condor and Seno Otway, however, strike-slip faults occur in the eastern part of Seno Otway and in Estuario Wickham (Figure 12). In Estuario Wickham, strike-slip faults occupy two dominant orientations. A set of west-striking faults is left-lateral and north-northeast-striking faults are right-lateral (Figures 12b-c). At site 11071 (Figure 12), a right-lateral fault crosscuts a back thrust, indicating that strike-slip deformation post-dates thrusting. Near Seno Otway, strike slip faults occupy similar orientations to those in Estuario Wickham. Sets of right-lateral faults strike northeast or north-northeast and left-lateral faults are west-striking (Figure 12d-h). Figure 12h shows an example of both right-lateral and left-lateral minor faults that are characteristic of those exposed near Seno Otway and Estuario Wickham. Displacements are on the order of centimeters to decimeters where they can be measured.

5.3 ANOMALOUS STRIKE-SLIP FAULTS

Southeastern localities: A relatively minor population (n=15) of strike-slip faults occurs along the Estrecho de Magallanes with shear senses that are opposite those of the dominant fault sets discussed above. East of Cabo Froward, three left-lateral faults strike northeast, and one right-lateral fault strikes northwest (Figure 13a). At Punta Brigida, three left-lateral faults strike northeast or north (Figure 13b). A set of five faults near Bahía del Indio (Figure 13c) and three faults near Bahía del Aguila (Figure 13d) consist

of right-lateral faults striking southeast and left-lateral faults striking northeast (Figures 13a-d). Crosscutting relationships between the dominant and anomalous sets of faults were only observed in two localities at site 10315 (location in Figure 13). Here, two northeast-striking right-lateral faults from the dominant set crosscut southeast-striking right lateral-faults of the anomalous set. On this basis, it is inferred that the dominant set of right- and left-lateral faults discussed above (*i.e.* Figure 9) are everywhere younger than the anomalous set discussed here (*i.e.* Figure 13). Faults from this population were not observed elsewhere in the study area.

5.4 NORMAL FAULTS

Southeastern localities: A small population (n=13) of normal faults occurs along the Estrecho de Magallanes between Cabo Froward and Bahía del Aguila (Figure 14). At Cabo Froward, one minor normal fault crosscuts sheared ignimbrite deposits near the contact between the Tobífera and Zapata-Canal Bertrand Formations (Figure 14a). Along the shore of the Estrecho de Magallanes <5 km east of Cabo Froward, at least seven normal faults occur (*e.g.* Figure 14b). Striae have steep rakes on normal fault planes that indicate oblique slip. One east-northeast-striking and three northwest-striking faults have a left-normal sense of slip. Three northeast-striking faults have a right-normal sense of slip (Figure 14b). Near Punta Brigida, two west-striking normal faults have down-dip striae, and one northeast-striking oblique slip fault has a normal-right sense of shear (Figure 14c). Only two normal faults were observed north of Punta Brigida (Figure 14d). Here, an east-northeast-striking fault has a right-normal shear sense, and a northwest-striking fault has a left-normal sense of shear.

Central localities: A small population of normal faults also occurs at Estuario Silva Palma (Figure 11b-e). Normal faults occupy two west-striking orientations, one set dips moderately toward the south, and a second dips shallowly toward the north to form a conjugate-style geometry. Striae have both down-dip and oblique rakes on normal fault planes (Figures 11b, c). At site 11055 (Figure 11), a set of minor brittle faults with normal-sense displacements offsets the contact between a silicic dike that intrudes psammitic schist of the Cordillera Darwin Metamorphic Complex. Both the dike and the psammite share a subsolidus foliation that is interpreted to reflect the first phase of

Andean thrusting (S_I , Figure 11e; Betka et al., 2015), indicating that normal faulting postdated contraction. Normal faults were not observed in northwestern localities.

6. Results: Test for kinematic compatibility among fault sets

6.1 THRUST FAULTS

Thrust faults are subparallel to one another throughout the study area and form two groups on the basis of orientation (Figure 15a-e). The majority dip dominantly toward the southwest and contain down-dip or steeply oblique striae. A subsidiary northeast-dipping set of faults occurs that forms a conjugate orientation with the main set and also contains steeply oblique striae. Shortening axes are subhorizontal and trend northeast, and extension axes are subvertical. It is clear that thrust faults have a dominant orientation that dips shallowly toward the southwest and contains striae with high-angle rakes on the fault surfaces. Kinematic axes from the total population ($n=87$) of thrust faults form point maxima indicating that they show kinematic homogeneity throughout the study area. Shortening axes are subhorizontal and trend northeast. Extension axes are subvertical. The plunge and trend of mean principal strain axes calculated by the linked Bingham method are 1) extension = 79° , 216° ; 2) intermediate = 4° , 325° ; and 3) shortening = 11° , 056° . Directional maxima calculated separately for shortening and extension axes are 12° , $056^\circ \pm 05^\circ$ and 79° , $212^\circ \pm 05^\circ$, respectively, indicating a good fit to the data (Figure 15f). Shortening and extension axes are compatible with the regional trends of contractional structures of the Cretaceous to Paleocene Magallanes fold-thrust belt (Betka et al., 2015).

6.2 STRIKE-SLIP FAULTS

Strike-slip faults occupy two dominant orientations in central and northwestern localities near Canal Jeronimo and Seno Otway (Figure 16a), Estuario Wickham (Figure 16b) and Estuario Silva Palma (Figure 16c). North to northeast-striking faults sets are all right-lateral, northwest- and east-northeast-striking sets are left-lateral. Striae are always moderately to shallowly plunging on fault surfaces, indicating a small component of

575 either normal or reverse displacement that depends on the dip-direction of the fault
576 surface and plunge direction of the slickenline. Kinematic axes from strike-slip fault
577 populations near Canal Jeronimo, Seno Otway, Estuarios Wickham and Silva Palma are
578 subparallel. Shortening axes plunge generally northeast and southwest; extension axes
579 plunge generally northwest and southeast (Figures 16a-c).

580 In southeastern localities, two populations of strike-slip faults occur near Cabo
581 Froward and the Estrecho de Magallanes. The dominant set ($n=105$) is subparallel to
582 strike-slip faults elsewhere in the study area. Right-lateral faults all strike northeast, and
583 left-lateral faults strike east-northeast, forming a conjugate-style set, or northwest.
584 Shortening axes from this population generally plunge shallowly east-northeast or west-
585 southwest; extension axes generally plunge shallowly north-northwest and south-
586 southeast (Figure 16e). The anomalous set of strike-slip faults ($n=15$) have opposite
587 senses of shear for their orientations compared with the dominant population (Figure
588 16d). For this reason the kinematic axes from this population of faults is also opposite to
589 those of the dominant set.

590 The attitudes of faults and striae, as well as the orientations of kinematic axes,
591 from the dominant set of faults near Cabo Froward and the Estrecho de Magallanes (*i.e.*
592 Figure 16e) are generally parallel to those elsewhere in the study area (Figure 16f). The
593 total population of strike-slip faults in the study area ($n=128$, excluding the anomalous
594 set) is kinematically homogeneous based on the subparallelism of shallowly plunging
595 kinematic axes that form statistically distinct point maxima defined by north-northwest-
596 trending extension axes and east-northeast-trending shortening axes (Figure 16f). The
597 plunge and trend of the mean principal strain axes calculated by the linked Bingham
598 method are 1) extension = $01^\circ, 339^\circ$; 2) intermediate = $81^\circ, 244^\circ$; and 3) shortening =
599 $09^\circ, 070^\circ$ (Figure 16f). Directional maxima calculated separately for shortening and
600 extension axes are $07^\circ, 070^\circ \pm 06^\circ$ and $02^\circ, 340^\circ \pm 06^\circ$, respectively, and indicate a good
601 fit to the data.

602 Right- and left-lateral strike-slip faults from the dominant population form a
603 conjugate set such that right-lateral faults have a mean strike of 030° and left-lateral
604 faults have a mean strike of 085° . A small sub-population of left-lateral faults strikes
605 toward 300° (Figure 17a). The orientations and sense of slip of the dominant faults are

sympathetic with the predicted attitudes and shear senses expected for a population of faults that form Riedel shears. Northeast-striking right-lateral faults form R'-shears and east-northeast striking left lateral faults form R-shears. The small set of northwest-striking left-lateral faults has an orientation consistent with P-shears (Figure 17a). Tensile calcite veins associated with strike-slip faults exposed along the Estrecho de Magallanes trend dominantly northeast and have a mean strike of 043° (Figure 17b) that is subparallel to the expected orientation of T-shears. The orientations of R-, R'-, P- and T-shears in the study are compatible with a principal fault plane that strikes west-northwest ($\sim 280^{\circ}$) and has a left-lateral sense of slip. The predicted principal fault zone is parallel to the trend of the Magallanes-Fagnano fault system ($\sim 275^{\circ}$ near Tierra del Fuego and $\sim 300^{\circ}$ in the Estrecho de Magallanes, Figure 1), thus strongly suggesting a genetic relationship between strike-slip faulting in the study area and the development of the Magallanes-Fagnano fault system.

6.3 NORMAL FAULTS

Normal faults in the study area were only observed in southeastern and central localities near Estuario Silva Palma or along the Estrecho de Magallanes (Figure 18a-b). In both locations they occupy three common orientations that strike west, northeast or northwest. Normal faults commonly dip steeply ($\sim 60^{\circ}$) and form conjugate-style sets that contain steeply plunging to oblique striae on the fault surfaces (Figure 18a-c). Kinematic axes from all normal faults in the study area form moderately defined point maxima such that shortening axes are subvertical, and extension axes are subhorizontal and north- or south-plunging. The plunge and trend of principal kinematic axes of normal faults calculated by the linked Bingham method are 1) extension = 05° , 183° ; 2) intermediate = 01° , 273° ; and 3) shortening = 85° , 013° (Figure 18c).

7. Discussion

7.1 RELATIVE TIMING OF NORMAL, STRIKE-SLIP AND THRUST FAULTS

Cross-cutting relationships clearly show that strike-slip faults everywhere overprint F_I folds and thrusts from the Magallanes fold-thrust belt (*i.e.* Figure 10a, c),

635 indicating the strike-slip deformation is younger. Although the shortening axes of strike-
636 slip faults are subparallel to those of thrust faults, the extension axes are perpendicular
637 (Figure 18e), thus negating complete kinematic compatibility. Additionally, structures
638 exposed in the foreland fold-thrust belt along the northeastern segment of transect A-A'
639 are upright with subvertical axial planar cleavages (S_1) in contrast to southwest-dipping
640 inclined folds that occur along strike near Seno Otway (Betka et al., 2015) and along the
641 southwest part of transect A-A'. For example, folds within the Canal Bertrand and
642 Latorre Formations on the southwestern part of A-A' trend north—northwest and have
643 moderately inclined axial planar cleavage (Figure 4c-f). In contrast, folds that crop out on
644 the northeastern segment of A-A' that were initially formed with respect to adjacent
645 thrust faults, now have subvertical axial planar cleavage and trend northwest (Figure 4g-
646 j). We interpret the upright fold orientations along the northeast segment of transect A-A'
647 to reflect a Neogene left-lateral strike-slip overprint on the Late Cretaceous-Paleogene
648 thrust belt that rotated northeast-vergent folds ~ 10 - 15° counterclockwise and tightened
649 them into upright orientations. We postulate the counterclockwise rotation of fold axes
650 and tightening of the limbs defines a local restraining bend where the map trace of the
651 Magallanes-Fagnano fault system curves toward the northwest and forms a splay across
652 Isla Dawson and Peninsula Brunswick (Figure 2, discussed below).

653 Minor normal faults were only observed in close proximity to strike-slip faults. In
654 many cases oblique-slip normal faults have the same strike-slip component of shear as
655 parallel sets strike-slip faults discussed above. For example, east of Cabo Froward, the
656 northwest-striking set of normal faults has a component of left-lateral slip, consistent
657 with northwest-striking strike-slip faults from the same location (*i.e.* Figures 9b, 14b).
658 Similarly, northeast-striking normal faults in this locality have a component of right-
659 lateral slip, consistent with the set of right-lateral faults that also strike northeast (*i.e.*
660 Figures 9b, 14b). Extension axes for normal fault populations plunge northward and
661 southward, similar to the north-northwest and south-southeast plunges of those from the
662 dominant set of strike-slip faults in the study area (Figure 18e), indicating a degree of
663 kinematic compatibility between strike-slip and normal fault sets. Thus, it is interpreted
664 that strike slip and normal faults are kinematically related and reflect a phase of bulk
665 transtensional strain (*c.f.* Klepeis, 1994; Lodolo *et al.*, 2003; Menichetti *et al.*, 2008). The

interpretation of bulk transtensional strain with the Magallanes-Fagnano fault system is also consistent with the results of a paleoseismology study of a fault scarp near Lago Fagnano that formed during two Ms. 7.8 earthquakes in 1949 (Costa et al., 2006). This study found evidence for at least two, possibly three, slip events prior to the 1949 earthquake that occurred in the last 8 kyr. The sense-of-slip for all of the events include both normal and strike-slip components of displacement and are consistent with a local releasing bend in the fault (Costa et al., 2006).

Consistent with the interpretation that strike-slip and normal faults are younger, the deformation conditions for strike-slip and normal faults were not the same as those for thrust faults. Many thrust faults in the study are defined by subsolidus quartz and feldspar foliations and recrystallized quartz stretching lineations (*e.g.* those at Bahía Fortesque, Figure 6d, thrust fabric that is cross-cut in Figure 11e), indicating deformation temperatures >300°C (see Betka, 2013). In contrast, all strike-slip and normal faults observed are brittle shear fractures indicating that they formed under much cooler deformation conditions and probably shallower levels of the crust, thus requiring substantial exhumation of the thrust belt to have occurred prior to the onset of strike-slip deformation. On the basis of crosscutting relationships and deformation conditions for each set of faults, it is deduced that strike-slip- and normal- faulting probably initiated during the Oligocene after the main pulse of Late-Cretaceous to Eocene contractional deformation ceased (*c.f.* Klepeis, 1994; Klepeis and Austin, 1997; Torres Carbonell *et al.*, 2008) and significant exhumation of the fold-thrust belt occurred (Fosdick *et al.*, 2013).

The small population (n=15, Figure 18d) of anomalous strike-slip faults exposed near the Estrecho de Magallanes is not kinematically compatible with any other fault set in the study area. The kinematic axes from these faults reflect north-south shortening and east-west extension (Figure 18d). Bingham analysis indicates that the intermediate principal strain axes of both sets of strike slip faults are subparallel however, the shortening and extension axes of the anomalous set occur ~65° CCW from those of the dominant set (Figure 18e). It is possible that the anomalous set of strike-slip faults reflects the earliest motions of sinistral strike-slip deformation associated with the Magallanes-Fagnano fault system and records north-trending shortening and east-trending extension that occurred in a restraining bend that developed near the northwest-

striking segment of the Magallanes-Fagnano fault zone near Bahía del Indio. This interpretation is supported by the observation that northeast-vergent inclined folds of bedding that are common in the fold-thrust belt are tighter and occur in more upright orientations near the map trace of strike-slip faults at Bahía del Indio, suggesting transpressional deformation along the fault (discussed above, Figure 3, 4). Furthermore, the dominant set of strike-slip faults that is kinematically compatible with normal faults crosscuts the anomalous set, indicating that transtensional deformation is younger. This interpretation is favored because these faults constitute a minor subset (6%) of the total population of faults observed.

7.2 SPATIAL DISTRIBUTION OF STRIKE-SLIP AND NORMAL FAULTS, IMPLICATIONS FOR EXTENT OF THE MAGALLANES FAULT SYSTEM

Strike-slip deformation is heterogeneously distributed throughout the study area. The highest density of strike-slip faults occurs along the Estrecho de Magallanes, probably because of their close proximity to the of the Magallanes-Fagnano fault system (*e.g.* Figures 9, 19). Winslow (1982) used areal photos to identify several young (Quaternary?) fault scarps that she interpreted as left-lateral splays from the Magallanes fault system. One splay transects Isla Dawson and trends northwest toward Peninsula Brunswick (Figure 19). A second fault scarp truncates stream meanders of the Río San Juan, located on Peninsula Brunswick north of the study area (Figure 19). New data presented in this study discerns a high-density of minor strike-slip faults near Bahía del Indio and Bahía Aguila that are kinematically compatible with a left-lateral, west-northwest striking principal fault zone. Bahía del Indio is exactly along the strike of the trace of the fault splay on Isla Dawson interpreted by Winslow (1982), and, thus, minor faults in the area are probably associated with this same structure (Figure 19).

Subsurface seismic data collected along the north-trending segment of the Estrecho de Magallanes between Isla Dawson and Peninsula Brunswick (Figure 19) confirm the occurrence of a steeply southwest-dipping fault plane along strike from Bahía del Indio and the map trace of a the fault picked by Winslow (1982) (Seismic data in Klepeis and Austin, 1997 and Lodolo *et al.*, 2003; locations shown in Figure 19). Lodolo

727 *et al.* (2003) interpret a component of normal top-down-to-the-southwest displacement in
728 addition to left-lateral shear based on growth strata that fill a small graben in the hanging
729 wall of the fault (Figure 15 of Lodolo *et al.*, 2003). Similarly, Klepeis and Austin (1997)
730 interpret normal-sense offset of bright reflectors between 1 and 5 second TWT.
731 However, the data are not migrated because of problems with seafloor reverberation and
732 sidewall echoes making the actual position of the reflectors somewhat ambiguous (Figure
733 6 of Klepeis and Austin, 1997). These seismic interpretations conflict with field mapping
734 along the shore of Peninsula Brunswick near Bahía del Indio. Here, the stratigraphic
735 separation across the fault requires a substantial reverse component of motion on a
736 southwest-dipping fault that we interpret to be a thick-skinned second-generation
737 basement uplift with ~3 km of throw (Figure 3, 4). A possible explanation for the
738 apparently conflicting interpretations lies in knowing the age of the reflectors that are
739 interpreted by Lodolo *et al.* (2003) and Klepeis and Austin (1997). The former authors
740 had interpretable seismic resolution to 1 second TWT, and the sediment water interface is
741 located at 0.8 second TWT, suggesting that the growth strata in the fault graben are
742 probably very young (Quaternary?, Lodolo *et al.*, 2003). On the basis of field mapping
743 along the shore of Peninsula Brunswick that requires a substantial component of reverse
744 motion on the fault (~3 km of throw), our favored interpretation is that a high-angle
745 Cretaceous reverse fault was reactivated by the left-normal slip described by Klepeis and
746 Austin (1997) and Lodolo *et al.* (2003). This interpretation is consistent with field
747 observations from this study that indicate strike-slip faults consistently crosscut
748 contractional structures of the Magallanes fold-thrust belt as well as recent seismicity
749 (Pelayo and Wiens, 1989) and geodetic data (Smalley *et al.*, 2003) that indicate left-
750 lateral deformation is presently occurring.

751 The map trace of the reverse fault near Bahía del Indio is inferred to continue for
752 ~100 km toward the northwest, where it crops out again at Seno Otway (Figure 19). Here,
753 strike-slip deformation is localized in the eastern part of the map area (*i.e.* Figure 12) near
754 Seno Otway and Estuario Wickham. Faults from these locations are kinematically
755 compatible with the population of Riedel shears that form under bulk left lateral shear
756 (*i.e.* Figure 17). For this reason, it is inferred that minor strike-slip faults that occur near
757 Seno Otway and Estuario Wickham are Riedel shears associated with left-lateral slip

758 along the Bahía del Indio fault, suggesting that left-lateral deformation persists
759 northwestward across Peninsula Brunswick along the Bahía del Indio fault for ~100 km
760 farther than previously mapped. On the basis of the much lower density of strike-slip
761 deformation near Seno Otway than the Estrecho de Magallanes, we infer that the fault
762 probably loses its strike-slip component of displacement toward the northwest (Figure
763 19). Strike-slip faults also occur in Seno Condor northwest of Canal Jeronimo. Here, we
764 interpret them to reflect a left-lateral splay fault from the Magallanes-Fagnano fault
765 system toward the south that probably formed along the boundary between the
766 Patagonian Batholith and mafic rocks of the Rocas Verdes basin, which may have
767 localized strain (Figure 12a, 19).

768 Figure 19 shows map traces of three east-northeast- or northeast-striking faults
769 that are inferred from topographic lineaments or from changes in the depth of exposure
770 across a fiord (i.e. Canal Jeronimo, see Betka, 2013). The faults are inferred to have
771 normal-sense displacements based on their orientation relative to the Magallanes-
772 Fagnano fault system, the strikes of minor normal faults presented in this study (Figure
773 18c). Northeast-striking normal faults are located between overlapping strands of the
774 Magallanes-Fagnano fault and the Bahía del Indio fault and strike ~45° counterclockwise
775 to the strike-slip faults, thus occupying the expected orientation for a system of normal
776 faults that formed between two strands of a left-stepping left lateral fault system (Figure
777 19, see inset). On this basis, we conclude that the Magallanes-Fagnano fault segment in
778 the Estrecho de Magallanes south of Peninsula Brunswick and the newly mapped Bahía
779 del Indio fault strand form a left-stepping, left-lateral fault segment from Isla Dawson to
780 Seno Otway. Thus the study area on Peninsula Brunswick occurs in releasing zone of the
781 Magallanes-Fagnano fault system. This interpretation is consistent with fault kinematic
782 results from strike-slip and normal fault sets in the study area near Estuario Silva Palma,
783 Cabo Froward and the Estrecho de Magallanes that are apparently coeval and record left-
784 lateral shear along a northwest striking fault system and north-south extension (Figures
785 16, 18c, e, 19). Left-stepping releasing segments of the Magallanes-Fagnano fault system
786 are well documented near Mt. Hope and Lago Fagnano and Isla Dawson (Klepeis and
787 Austin, 1997; Lodolo *et al.*, 2003; Menichetti *et al.*, 2008), and near Isla Desolación

788 along the Pacific margin of Chile (Lodolo *et al.*, 2003), indicating that transtensional
789 deformation occurred in many places along the Magallanes-Fagnano fault system.

790 Strain within continental transform systems is commonly localized on faults that
791 form along antecedent geological boundaries such as rigid blocks or sutures (e.g. Bennett
792 *et al.*, 2003; Thatcher, 2007; Şengör *et al.*, 2005). Hervé *et al.* (2010) postulated that the
793 Magallanes Fagnano fault system reactivated a pre-Jurassic suture zone between
794 basement terranes of Tierra del Fuego and the Cordillera Darwin. This interpretation is
795 consistent with the findings of Lodolo *et al.* (2003) who document several transtensional
796 basins that developed along the Magallanes-Fagnano fault system on Isla Grande de
797 Tierra del Fuego and Lago Fagnano where the fault zone separates lithotectonic domains
798 of the Cordillera Darwin and Rocas Verdes basin to the south from cretaceous rocks of
799 the Magallanes basin to the north. However, Lodolo *et al.* (2003) also document young
800 (Quaternary) pull-apart basins along the fault zone within the northwest-trending segment
801 of the Estrecho de Magallanes. Here, the fault zone separates rocks of the Patagonian
802 Batholith (southwest) from the Cordillera Darwin and Rocas Verdes Terranes toward the
803 north. We postulate that the Bahía del Indio fault reflects a northwest-striking splay of the
804 eastern segment of the Magallanes Fagnano fault system that separates terranes with
805 Cordillera Darwin and Rocas Verdes basement from those with pre-Jurassic basement to
806 the northeast. We suggest that the main strand of the fault stepped west-northwestward
807 across the Rocas Verdes terrane and localized along the boundary with the Patagonian
808 Batholith (Figure 19). This interpretation is consistent with the observation that the Bahía
809 del Indio fault reactivates a high-angle basement involved reverse fault of the Late
810 Cretaceous—Paleogene Patagonian fold-thrust belt and suggests that the inherited
811 architecture of the basement terranes and structure of the fold-thrust belt defined a
812 mechanical anisotropy that influenced the partitioning of strain within the Magallanes
813 Fagnano fault zone.

814 **7.3 TIMING OF TRANSTENSION**

815 Crosscutting relationships presented in this paper are consistent with those
816 reported by many authors (*e.g.* Klepeis *et al.*, 1994; Klepeis and Austin, 1997; Lodolo *et*
817 *al.*, 2003; Menichetti *et al.*, 2008; Torres Carbonell, 2008) that indicate strike-slip

deformation overprints the Late-Cretaceous to Eocene retroarc fold-thrust belt. Fault kinematic data from strike-slip and normal faults in this study reflect bulk transtensional strain within the Magallanes-Fagnano fault zone that is superimposed on the thrust-belt (Figure 18e, 19). Although zones of transpression occur where geometry of the fault system causes local contraction, such as the restraining bend near Bahía del Indio (Figure 3, 19), the population of thrust faults that record regional crustal shortening and thickening during the development of the Patagonian fold-thrust belt are older (e.g. Figure 3, 11e). Altogether, the fault kinematic data and cross-cutting relationships presented in this study indicate that crustal thickening during the development of the Patagonian fold-thrust belt occurred prior to the onset of strike-slip deformation and transtension.

Although the absolute timing of the onset of strike-slip deformation in the southernmost Andes is not well constrained, most authors agree that sinistral transtension has occurred dominantly since Oligocene time (e.g. Klepeis, 1994; Lodolo *et al.*, 2003; Menichetti *et al.*, 2008) and probably shares a genetic relationship with the opening of the Drake Passage and development of the Scotia Plate (e.g. Barker, 2001; Geletti *et al.*, 2005; Lodolo *et al.*, 2006). Time-constrained balanced cross sections of the Fuegian retroarc thrust belt indicate that the last pulse of thrusting occurred during the Late Oligocene or Early Miocene (Torres Carbonell *et al.*, 2011). These authors report that contractional structures of the Fuegian fold and thrust belt are offset by ~48km of sinistral displacement across the Magallanes-Fagnano fault system, indicating a maximum Miocene age for the development of the fault system based on the age of offset strata. The Miocene age for the onset of strike-slip deformation, magnitude of offset, and crosscutting relationships, are consistent with an extrapolation of the present slip-rate (~6.6 mm/yr after Smalley *et al.*, 2003) combined with the obtained offset to ~7 Ma. (Torres Carbonell, 2008; *c.f.* Lodolo *et al.*, 2003). A Miocene age for the onset of strike-slip deformation on Tierra del Fuego coincides with a widespread pulse of uplift and exhumation of the Patagonian fold-thrust belt near Ultima Esperanza (Fosdick *et al.*, 2013) and the emergence of the North Scotia Ridge and islands of Tierra del Fuego (Barker, 2001; Eagles, 2005; Lagabrielle *et al.*, 2009), suggesting a regional response to

changes in the tectonic setting of the Scotia Arc during the opening of the Drake Passage and development of the West Scotia Sea (*c.f.* Dalziel *et al.*, 2013).

8. Conclusions

Fault slip data collected over a ~100 km² of the Magallanes retroarc fold thrust belt near Peninsula Brunswick and Seno Otway fall into four well-defined populations: 1) thrust faults strike northwest and have subhorizontal, northeast-trending shortening axes; 2) a dominant set of strike-slip faults form conjugate pairs that consist of northeast-striking right-lateral faults and east-northeast left-lateral faults as well as less common northwest-striking left-lateral faults; 3) normal faults that strike east to east-northeast and northwest and have subhorizontal north- or south-plunging extension axes; 4) an anomalous set of strike-slip faults consisting of northeast-striking left-lateral faults and northwest-striking right lateral faults that is crosscut by the dominant set.

Strike-slip faults form Riedel, T- and P-shear geometries and have subhorizontal east-northeast trending shortening axes, kinematically compatible with the west-northwest-trending map trace of the sinistral Magallanes-Fagnano fault system. A population of oblique-slip normal faults is kinematically compatible with strike-slip faults of the dominant set and together both fault sets reflect regional bulk transtension. An older, subsidiary set of left- and right-lateral strike-slip faults is crosscut by the dominant set and has horizontal shortening axes that trend northward. The subsidiary set is interpreted to reflect the earliest stages strike-slip motion and to reflect north-trending shortening in a restraining bend.

A newly mapped left-lateral fault segment named the Bahía del Indio fault strikes northwest for ~100 km across Peninsula Brunswick between the Estrecho de Magallanes and Seno Otway. The map trace of this fault is continuous with a prominent lineament that appears in areal photographs and satellite imagery on Isla Dawson (Winslow, 1982) and a left-normal fault that appears in reflection seismic data below the Estrecho de Magallanes (Klepeis and Austin, 1997; Lodolo *et al.*, 2003), indicating that the Bahía del Indio fault is part of the Magallanes-Fagnano fault system. The southwestern end of

Peninsula Brunswick occurs in a left-lateral, left-stepping releasing zone between the Bahía del Indio fault and the Magallanes-Fagnano fault trace in the northwestern trending segment of the Estrecho de Magallanes.

Strike-slip and normal faults either crosscut or reactivate reverse faults and contractional folds of the Magallanes retroarc fold-thrust belt everywhere they were observed, indicating that the onset of strike-slip deformation on Peninsula Brunswick postdates the Late-Cretaceous – Eocene fold-thrust belt. Crosscutting relationships and fault kinematic data from Peninsula Brunswick support a growing body of literature that place the Magallanes-Fagnano fault system in a tectonic framework defined regional sinistral transtension that occurred in response to the opening of the Western Scotia Sea and the Drake Passage during the Early Miocene.

The Magallanes-Fagnano fault system is an example of how strike-slip displacement from a plate-bounding strike-slip fault zone is diffusely distributed within a pre-existing fold-thrust belt. The main strands of the Magallanes-Fagnano fault zone developed along sutures between basement terranes of Tierra del Fuego, the Cordillera Darwin, Rocas Verdes Basin and Patagonian Batholith (*c.f.* Hervé et al., 2010). Slip was distributed and partitioned within the thrust belt onto splay faults, such as the Bahía del Indio fault, that reactivated reverse faults of the Patagonian fold-thrust belt and were localized along a mechanical anisotropy defined by the structural trend of the orogen. Subsidiary sets of strike-slip and normal faults that are kinematically compatible with both restraining bends (i.e. the anomalous set) and releasing step-overs (i.e. normal faults) formed to accommodate strain between main splays of the fault system.

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1315

Figure captions

1316 Figure 1. Shaded relief image of the southernmost Andes compiled from SRTM 30m
1317 topography data. Location of the study area is shown. Pink and blue shading
1318 highlights the outcrop extent of rocks from the Rocas Verdes basin and
1319 Cordillera Darwin metamorphic complex, respectively (modified after
1320 Klepeis *et al.*, 2010 and Torres Carbonell *et al.*, (2013)). Red lines indicate
1321 map trace of the Magallanes-Fagnano and Beagle Channel fault systems
1322 after Cunningham (1993), Klepeis, (1994), Klepeis and Austin (1997),
1323 Smalley *et al.* (2003), Lodolo *et al.* (2003), and Esteban *et al.* (2014). Thick
1324 black line represents location of trench between the Antarctic and Scotia
1325 plates, teeth on overriding plate. Inset, physiography of the Scotia Arc
1326 region showing major plate bounding structures after Dalziel *et al.* (2013)
1327 and Smalley *et al.* (2003). Bold black lines are subduction zones with teeth
1328 in the upper plate, solid black lines are transform faults and dashed red lines
1329 are modern spreading centers. Abbreviations as follows: SAM, South
1330 American Plate; SCO, Scotia Plate; ANT, Antarctic Plate; MFFS,
1331 Magallanes-Fagnano fault system; BCFS, Beagle Channel fault system;
1332 NSR, North Scotia Ridge; SSR, South Scotia Ridge; SFZ, Shackleton
1333 Fracture Zone; SG, South Georgia Island; LF, Lago Fagnano; SA, Seno
1334 Almirantazgo; PB, Peninsula Brunswick; IR, Isla Reisco; IGTdF, Isla
1335 Grande of Tierra del Fuego; EdM, Estrecho de Magallanes; SO, Seno
1336 Otway. Data sources: Digital Elevation Model, Farr *et al.* (2007); inset
1337 basemap from GeoMapApp (<http://www.geomapapp.org>, Ryan *et al.*, 2009);
1338 1, Smalley *et al.* (2003).

1339

1340 Figure 2. Geologic map of Seno Otway and Peninsula Brunswick constructed from data
1341 collected in this study, Betka (2013), McAtamney *et al.* (2011). Unit names for
1342 Cretaceous sedimentary strata are from Castielli *et al.* (1993) and Mpodozis *et al.*
1343 (2007). The locations of figures 3-14 are shown as well as the locations of cross
1344 section line A-A'. CJ, Canal Jeronimo; EW, Estuario Wickham; ESP, Estuario
1345 Silva Palma; BF, Bahía Fortesque; CF, Cabo Froward.

1346

1347 Figure 3. Geologic map of Peninsula Brunswick near Cabo Froward showing data
1348 collected during this study. Black dot and corresponding number refers to data
1349 station mentioned in text. Data collected at 1:25,000 scale.

1350

Figure 4. (a) Cross section from A-A', see figure 3 for location. Short-dashed lines show schematic trace of bedding. Stereograms of structural data from five structural domains: (b) the Tobífera Formation at Cabo Froward, (c-d) the Zapata-Canal Bertrand Formation at Cabo Froward, (e-f) bedding orientations and folds within the Zapata-Canal Bertrand, Latorre, and Escarpada-Fuentes Formations near the pop-up structure, (g-h) folds within the Escarpada-Fuentes Formations in the foreland fold-thrust belt, and (i-j) folds within the Fuentes/Rocallosa Formation in close proximity to map-scale strike-slip faults.

Figure 5. Map showing spatial distribution and orientations of thrust fault populations and kinematic axes in the southeastern part of the study area near Cabo Froward and the Estrecho de Magallanes. (a) Field photograph showing F_1 folds within the Zapata-Canal Bertrand Formation near Cabo Froward that are truncated by thrust faults. (b, d-e, left) Equal area, lower hemisphere stereographic projections showing attitudes of fault surfaces (great circles) and striae (solid black dots). Arrows on striae shows motion of the hanging wall; (b, d-e, right) equal area stereographic projection showing attitudes of shortening (black dots) and extension (white dots) axes, linked Bingham axes (black squares: 1, extension; 2, intermediate; 3, shortening), and fault plane solution constructed from the linked Bingham axes (gray shaded areas show extension dihedra, white areas show shortening dihedra). (c) Rose diagram showing normalized distribution of trends of tensile calcite veins associated with thrust faults. Hereafter, all stereograms and rose diagrams are presented the same way unless otherwise indicated.

Figure 6. Map showing spatial distribution and orientations of thrust fault populations and kinematic axes in the central part of the study area near Estuario Silva Palma, Bahía Fortesque (BF) and Seno Cordes (SC). (a-d) Stereographic projections showing attitudes of faults and striae (left) and kinematic axes (right).

Figure 7. Map showing spatial distribution and orientations of thrust fault populations and kinematic axes in the northwestern part of the study area near Canal Jeronimo and Seno Otway, (left) faults and striae (right) kinematic axes.

Figure 8. Map showing spatial distribution and orientations of thrust fault populations and kinematic axes in the northwestern part of the study area near Estuario Wickham. (a-g) Stereographic projections showing attitudes of faults and striae (left) and kinematic axes (right).

Figure 9. Map showing spatial distribution and orientations of the dominant strike-slip fault populations and kinematic axes in the southeastern part of the study area near Cabo Froward and the Estrecho de Magallanes. (a-g) Stereographic projections showing attitudes of faults and striae (left) and kinematic axes (right). Rose diagrams in (b-d, f-g) show trends of tensile and sigmoidal calcite veins associated with the strike-slip faults in each location.

Figure 10. Field photographs showing examples of strike-slip faults near Cabo Froward (a) and the Estrecho de Magallanes (b-f). Faults are marked by broken lines and bedding (S_0) by dotted lines. (a) Strike-slip faults crosscutting deformed bedding of the Zapata-Canal Bertrand Formation near Cabo Froward, senses of displacement are apparent; here slip lineations are subhorizontal (see figure 6a), (b-c) conjugate sets of strike-slip faults near Bahía Rosa crosscutting strata of the Latorre (b, map view) and Escarpada (c) Formations, (d) map view of cataclasite in a ~5 m wide left-lateral fault zone at site 10338, (e-f) map view of conjugate sets of strike-slip faults displacing bedding of the Fuentes-Rocallosa Formations, short solid lines highlight trends of tensile calcite veins.

Figure 11. Map showing spatial distribution and orientations of strike-slip and normal fault populations and kinematic axes in the central part of the study area near Estuario Silva Palma, Bahía Fortesque and Seno Cordes. (a-c) Stereographic projections showing attitudes of faults and striae (left) and kinematic axes (right). (d-e) Field photographs of an outcrop face showing examples of brittle normal faults offsetting bedding (d) and a subsolidus S_1 foliation (e).

Figure 12. Map showing spatial distribution and orientations of strike-slip fault populations and kinematic axes in the northwestern part of the study area near Canal Jeronimo, Seno Otway and Estuario Wickham. (a-g) Stereographic projections showing attitudes of faults and striae (left) and kinematic axes (right). (h) Field photograph showing map view of a right-lateral strike-slip fault (horizontal trace in photo) with three subsidiary left-lateral faults. S_0 , bedding, field book for scale.

1426 Figure 13. Map showing spatial distribution and orientations of the anomalous strike-slip
1427 fault populations and kinematic axes in the southeastern part of the study
1428 area near Cabo Froward and the Estrecho de Magallanes. (a-d)
1429 Stereographic projections showing attitudes of faults and striae (left) and
1430 kinematic axes (right).

1431

1432 Figure 14. Map showing spatial distribution and orientations of normal fault populations
1433 and kinematic axes in the southeastern part of the study area near Cabo
1434 Froward and the Estrecho de Magallanes. (a-d) Stereographic projections
1435 showing attitudes of faults and striae (left) and kinematic axes (right).

1436

1437 Figure 15. Stereographic projections showing attitudes of faults and striae (left) and
1438 kinematic axes (right) from all thrust faults near (a) Canal Jeronimo and
1439 Seno Otway, (b) Estuario Wickham, (c) Estuario Silva Palma, (d) Seno
1440 Cordes and Bahía Fortesque, (e) Cabo Froward and the Estrecho de
1441 Magallanes and (f) all thrust faults in the study area. Black small circles in
1442 (f) are 95% confidence intervals for clusters of shortening (e_3) and extension
1443 axes (e_1), respectively.

1444 Figure 16. Stereographic projections showing attitudes of faults and striae (left) and
1445 kinematic axes (right) from all strike-slip faults near (a) Canal Jeronimo and
1446 Seno Otway, (b) Estuario Wickham, (c) Estuario Silva Palma, (d) Cabo
1447 Froward and the Estrecho de Magallanes, (e) all anomalous strike-slip faults
1448 and (f) all strike-slip faults from the dominant population in the study area.
1449 Black small circles in (e) and (f) are 95% confidence intervals for clusters of
1450 shortening (e_3) and extension axes (e_1), respectively.

1451 Figure 17. Kinematic synthesis of the dominant set of strike-slip faults, (a) rose diagram
1452 showing strikes of the dominant sets of right- and left-lateral faults in the
1453 study area, thick black line shows trend of predicted principle fault zone
1454 based on Riedel shear geometry, (b) rose diagram showing trends of tensile
1455 veins in the study area, (c) diagram synthesizing trends of right- and left-
1456 lateral faults as well as tensile veins according to Riedel shear theory, ellipse
1457 is a schematic strain ellipse and thick black arrows show expected
1458 shortening and extension directions.

Figure 18. Stereographic projections showing attitudes of faults and striae (left) and kinematic axes (right) from all normal faults near (a) Estuario Silva Palma, (b) Cabo Froward and the Estrecho de Magallanes, (c) all normal faults in the study area. (d) Stereograms showing attitudes of faults and striae (left) and kinematic axes (right) from all anomalous faults in the study area (n=15). (e) Equal area stereographic projection of linked Bingham axes calculated for the total normal fault population (solid circles), the total population of dominant strike-slip faults (solid squares), the population of anomalous strike-slip faults (solid diamonds), and the total population of thrust faults (solid triangles) in the study area. White symbols indicate principal extension axes, grey symbols indicate intermediate strain axes and black symbols indicate principal shortening axes.

Figure 19. Shaded relief image showing trace of the newly mapped Bahía del Indio fault and correlation with splay of the Magallanes-Fagnano fault system as mapped by 1, Winslow (1982); 2, Klepeis (1994); 3, Klepeis and Austin (1997) and 4, Lodolo *et al.* (2003). Thin black dashed lines show traces of northeast-striking normal faults inferred from the shaded relief image or from apparent changes in the depth of exposure that are observed (Betka, 2013). Locations of the two seismic lines discussed in text are shown with dashed lines. The geologic map of Peninsula Brunswick (as in Figure 2) is shown to demonstrate the superposition of strike-slip deformation along the trend of the Cretaceous-Paleogene fold-thrust belt. Gray shaded area highlights postulated extent of basement rocks from the Rocas Verdes and Cordillera Darwin terranes. Inset, schematic showing the development of a releasing step-over, modified after Twiss and Moores (2007). MFF, Magallanes-Fagnano fault; BdIF, Bahía del Indio fault; PB, Peninsula Brunswick; ID, Isla Dawson.

*Figure1-19

Figure 3

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Thrusts near Canal Jeronimo and Seno Otway

Thrusts near Estuario Wickham

Thrusts near Estuario Silva Palma

Thrusts near Seno Cordes
and Bahía Fortesque

Thrusts near Cabo Froward and
the Magallanes Straits

All thrust faults in study area

c.i. = 2 sigma

$e_3 - 056/12 \pm 05$

$e_1 - 212/79 \pm 05$

Figure 15

Canal Jeronimo and Seno Otway

Estuario Wickham

Estuario Silva Palma

Anomalous faults from Cabo Froward and the Magallanes Straits

Cabo Froward and Magallanes Straits

All strike-slip faults in dominant population

Figure 16

Figure 17

Normal faults near Estuario Silva Palma

Normal faults near Cabo Froward and the Magallanes Straits

All normal faults

Anomalous strike-slip faults near Cabo Froward and the Magallanes Straits

Bingham axes from fault sets

Figure 18

Figure 19