PERGAMON

Journal of Structural Geology 23 (2001) 1727–1739

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jstrugeo

Rapid creation and destruction of sedimentary basins on mature strike-slip faults: an example from the offshore Alpine Fault, New Zealand

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Received 31 January 2000; revised 5 March 2001; accepted 20 March 2001

Abstract

Seismic reflection profiles and multibeam bathymetric data are integrated to analyse the structure of the 25 km-long strike-slip Dagg Basin associated with the marine section of the Alpine Fault, Fiordland, New Zealand. The basin is developing in almost 3000 m water depth at a releasing bend, whilst contemporaneous transpression results in inversion of its southern end. Fiord-derived glacio-marine sediments flooded the basin during the last glaciation, and provide a stratigraphic framework for structural analysis. Geometrical analysis enables an estimation of 450–1650 m of dextral displacement on the Alpine Fault at the releasing bend since the development of an unconformity estimated to have formed at between 30 and 110 ka. This implies a dextral slip rate ranging from a possible minimum of 4 mm/yr to the maximum of 35 mm/yr constrained by the Pacific–Australian plate motion rate. Despite total dextral displacement of 480 km on the Alpine Fault zone and a growth history spanning 15–20 Myr, this geomorphically well expressed and structurally complex strike-slip basin developed and evolved rapidly during the late Pleistocene, and thus represents only the latest phase in the evolution of the Alpine Fault. Upward splaying structures within the fault zone exhibit a rapid spatial evolution in Pleistocene strata, which may reflect the interactions between high fault slip rate, voluminous sedimentation supply, inherited structural complexities in the basement rocks and deeper cover sequence, and interactions between adjacent faults. The present through-going releasing bend at the northern end of the basin may have evolved from a more complex pull-apart basin that developed between separate segments of the Alpine Fault. The results from Dagg Basin illustrate the rates at which structural complexities and sedimentary basins can develop within highly active, very mature, through-going continental wrench faults. Strike slip basins on the scale of 40–80 km^2 on such faults may be ephemeral features that can be developed and destroyed on a time scale of 10^5–10^6 years.

Keywords: Alpine fault; Strike slip; Continental; New Zealand; Fiordland; Marine; Active tectonics; Seismic reflection; Multibeam bathymetry; Sedimentary basin

1. Introduction

A variety of strike-slip sedimentary basins occur at plate boundaries, with structural styles that are a function of a number of variables including: the degree of divergence, convergence, and segmentation of the master fault traces; magnitude of total displacement; interactions between fault slip rate and sedimentation rate; age of the basin; physical properties of the deforming sediments and rocks; and the presence of pre-existing structures (Reading, 1980; Christie-Blick and Biddle, 1985; Sylvester, 1988). Field studies show that divergent strike-slip basins may form at the intersections of bifurcating faults, at stepovers between discontinuous master fault segments, and at releasing bends on continuous through-going faults (e.g. Crowell, 1974; Adyin and Nur, 1982; Mann et al., 1983; Christie-Blick and Biddle, 1985; Sibson, 1986; Deng et al., 1987; Cowan, 1990). Mann et al. (1983) considered that basin width is fixed by the original fault separation, and that the basins evolve through a series of stages. Numerical models (Rodgers, 1980) and recent laboratory analogue experiments also suggest that the evolving structure of a strike-slip basin may be strongly influenced by the initial geometry of the master-fault stepover (Dooley and McClay, 1997; Basile and Brun, 1999).

Some strike-slip basins have evolved over tens of millions of years (e.g. Reijs and McClay, 1998), whereas others have grown or changed rapidly over periods of 10^5–10^6 years (e.g., Sibson, 1986; Wood et al., 1994). In mature stages of development, pull-apart basins may become extinct, as new strike-slip faults develop obliquely across

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0191-8141/01/$ - see front matter
PII: S0191-8141(01)00044-X

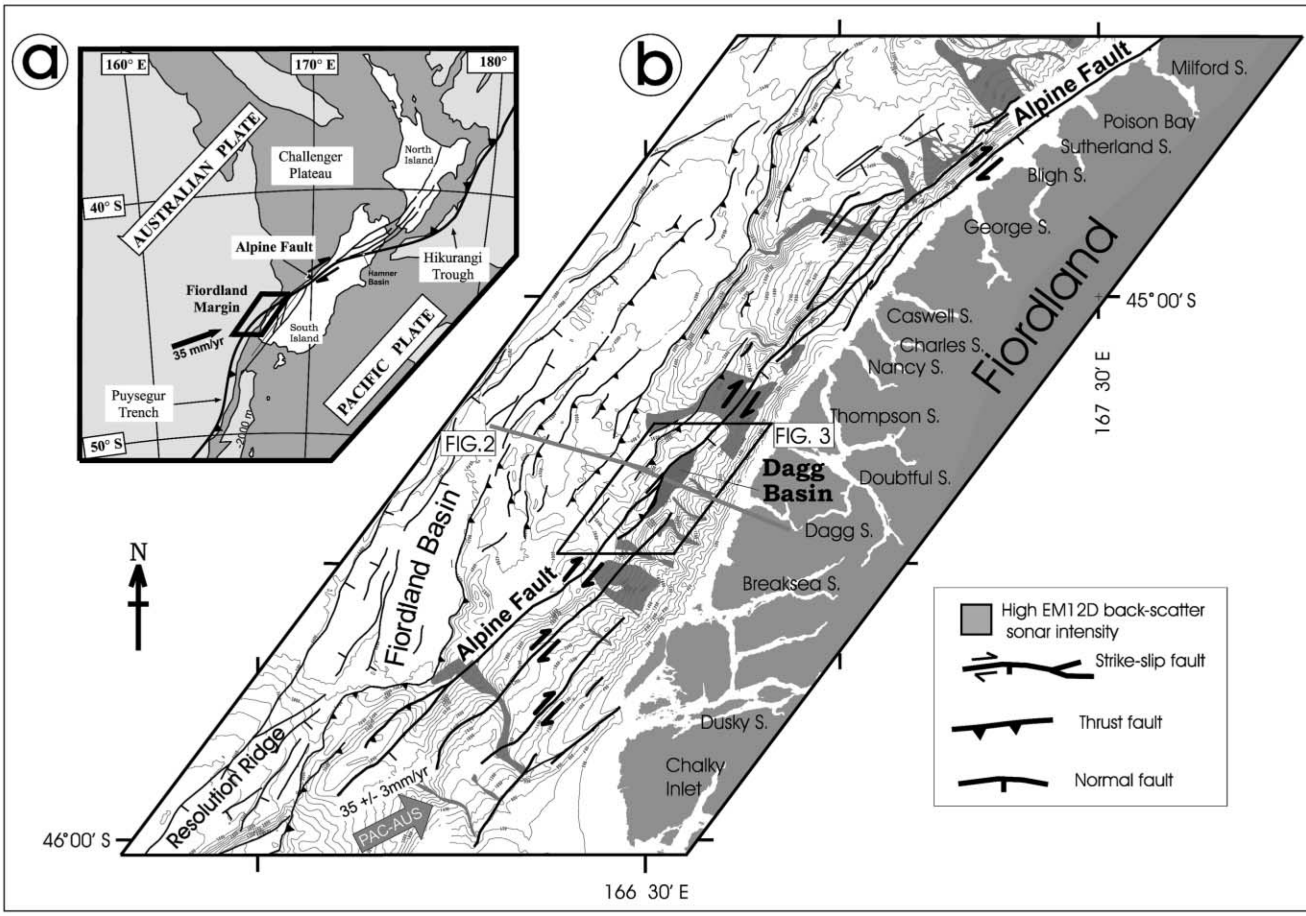

Fig. 1. (a) Major features of the Pacific–Australian plate boundary zone, showing the location of the Fiordland margin. Bold arrow indicates the motion of the Australian Plate relative to the Pacific Plate. (b) Regional structure map of the Fiordland margin and Alpine Fault, showing the location of Dagg Basin (modified from Lebrun et al. (2000)).

the basins, leading to a straightening of the principal displacement zone (Zhang et al., 1989; Dooley and McClay, 1997).

The large total dextral displacement (>400 km), high late Quaternary slip rate, prominent submarine geomorphic expression, proximity to rapid sediment supply, and accessibility of the southern, offshore section of the Alpine Fault in New Zealand to marine swath imagery and seismic reflection techniques makes it well suited to the study of 3-dimensional structure and strike-slip basin evolution.

In this paper we present the first structural study of a strike-slip basin associated with the offshore Alpine Fault, by integrating new multichannel seismic reflection profiles with existing EM12D multibeam bathymetry and back-scatter imagery data (Delteil et al., 1996b). The combined data set enables a 3-dimensional analysis of the structure and evolution of the basin. The bathymetric data provides details of the tectonic control on the seafloor morphology, whereas the seismic reflection profiles constrain the sub-surface geometry and temporal propagation of structures. We will demonstrate that the 25 km-long Dagg Basin (Fig. 1(b)) is currently developing at a releasing bend on the Alpine Fault, with contemporaneous uplift and inversion at its southern end. Our data indicate a youthful basin development and a surprisingly complex recent structural history for a mature through-going strike-slip fault zone with large displacement. Our results have implications for understanding of the rates of structural development and basin evolution within major, mature continental strike-slip fault systems.

2. Alpine fault

The Alpine Fault is a mature, 800 km-long dextral strike-slip fault presently accommodating 60–90% (26 ± 6 mm/yr) of the relative motion between the obliquely converging Pacific and Australian plates (Fig. 1(a)) (Wellman, 1953; Berryman et al., 1992; Sutherland and Norris, 1995). The fault is inferred to have begun activity in the Miocene, and has since accommodated up to 480 km of dextral displacement. The southern 300 km of the fault has been interpreted as an active, steeply-dipping continental wrench zone, in contrast to the moderately east-dipping transpressive structure that dominates the collision zone in central South Island (Norris et al., 1990; Berryman et al., 1992; Sutherland and Norris, 1995; Lebrun et al., 2000).

Strike-slip basins, lens-shaped uplifted slivers, en echelon

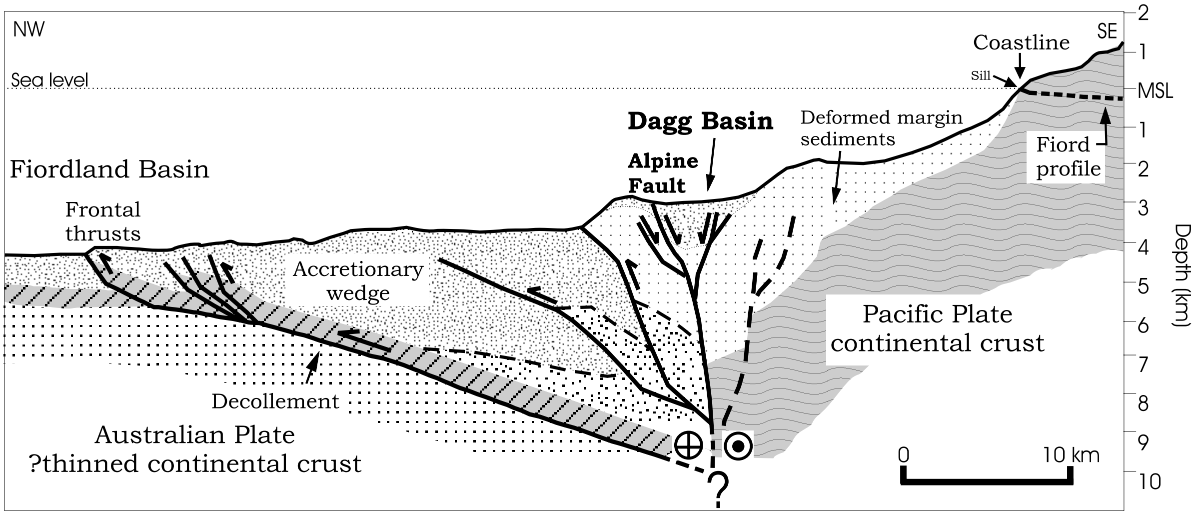

Fig. 2. Upper crustal schematic section through Dagg Basin and the lower margin accretionary wedge based on data fromWood et al. (2000). Location shown on Fig. 1(b).

ridges, and anastomosing fault traces were recently interpreted by Lebrun et al. (2000) from multibeam bathymetric data of the 230 km-long offshore section of the fault. The fault crosses the Fiordland coastline at the mouth of Milford Sound, and traverses very obliquely across the steep (typically c. 10°) continental margin to intersect the deformation front where Resolution Ridge terminates at the northern end of Puysegur Trench (Fig. 1(b)).

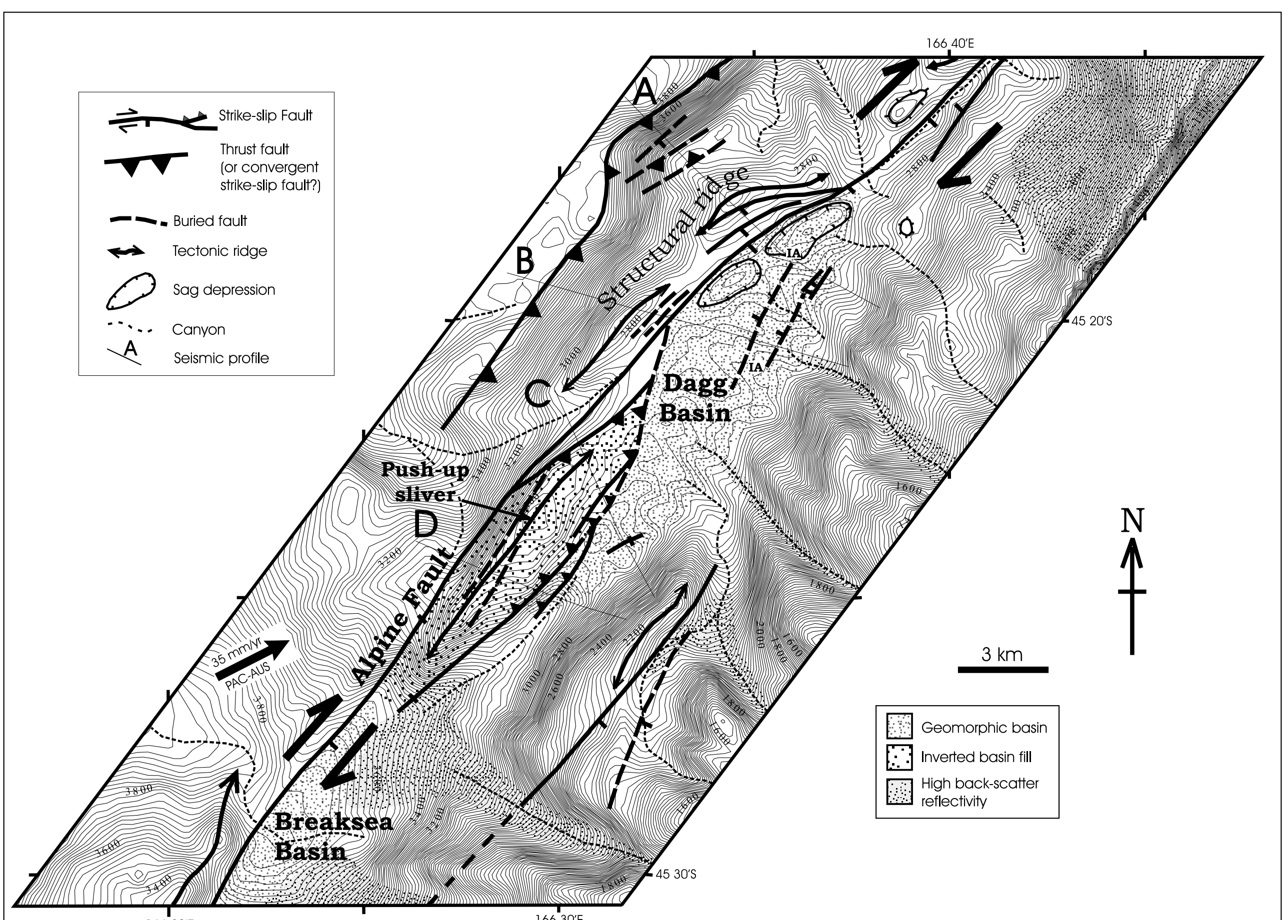

Fig. 3. Structure and tectonic geomorphology of Dagg Basin and surrounding region, interpreted from EM12D multibeam bathymetric data and multichannel seismic reflection profiles. The location of the map is shown in Fig. 1(b). Profiles A–D are presented in Figs. 4–7, respectively.

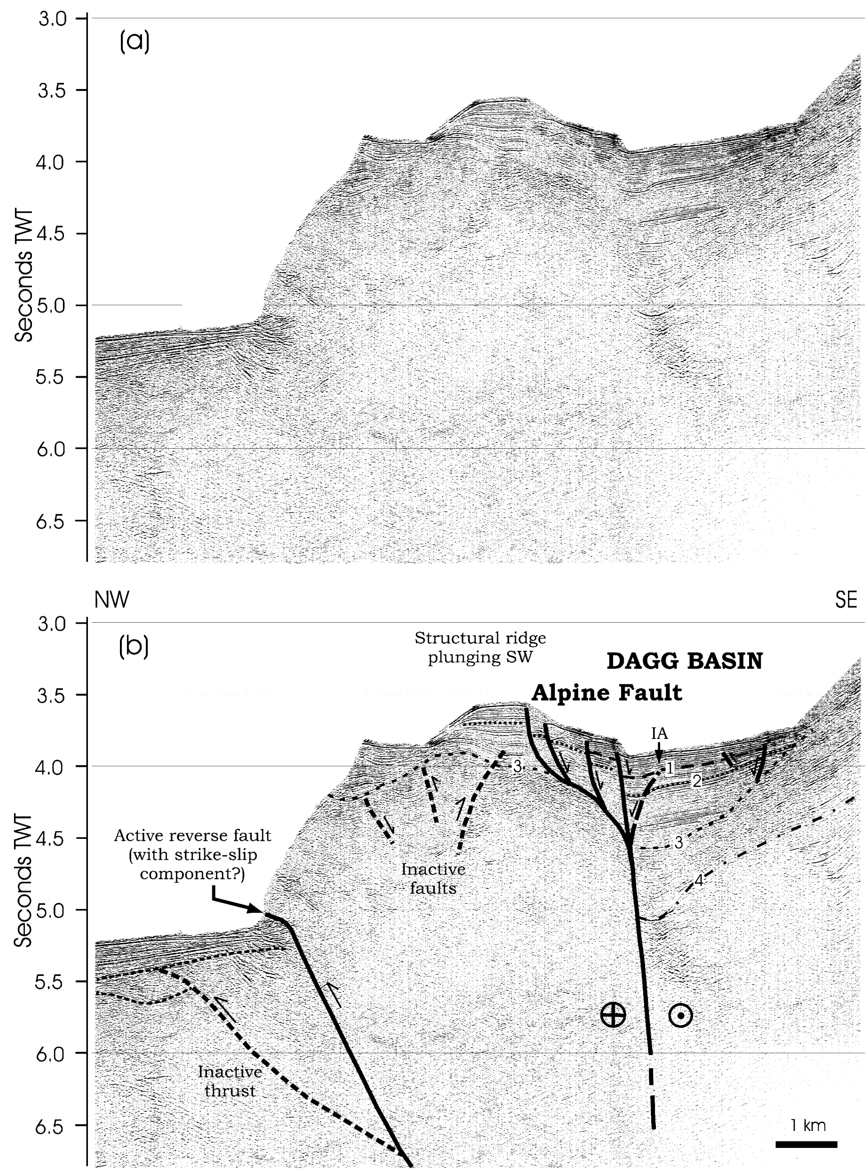

Fig. 4. Uninterpreted (a) and interpreted (b) migrated seismic reflection profile A across the subsiding, northern part of Dagg Basin, and the structural ridge to seaward. The location of the profile is shown in Fig. 3. Numbers labelling reflectors and faults are referred to in the text. Dashed faults are inactive. The profile (TA-11) is a 10-channel section acquired on R/V *Tangaroa.* Vertical exaggeration of the profile is 2.2:1 at a velocity of 2 km/s.

The present location of the Alpine Fault is thought to have been strongly influenced by the configuration of pre-existing structures (Delteil et al., 1996a, 1996b; Lebrun, 1997; Wood et al., 2000). In response to temporal variations in the relative motion between the Pacific and Australian plates, and an evolving plate boundary zone in southern New Zealand, the Fiordland margin has been the site of polyphase deformation for at least 15–20 Myr (Sutherland, 1995; Lebrun, 1997; Wood et al., 2000; Sutherland et al., 2000). Predominantly transcurrent motion through the Miocene has changed to oblique convergence during the Pliocene–Pleistocene. The average strike of the active trace of the fault in the vicinity of Dagg Basin is about 25° oblique to the azimuth of the current Pacific–Australian plate motion vector (DeMets et al., 1994). Some of the contractional strain that must be resolved normal to the plate boundary is accommodated to the west of the fault by décollement thrust faulting and frontal accretion beneath the lower margin, by reverse-slip structures at the rear of the accretionary wedge, and by thrust and reverse faulting east of Fiordland (Figs. 1 and 2) (Lebrun et al., 2000).

3. Seismic reflection data

New multichannel seismic reflection profiles were acquired on R/V *Tangaroa* in 1997. The acquisition system comprised a 45/105-capacity GI gun seismic source, a 16-channel streamer with hydrophone group spacing of

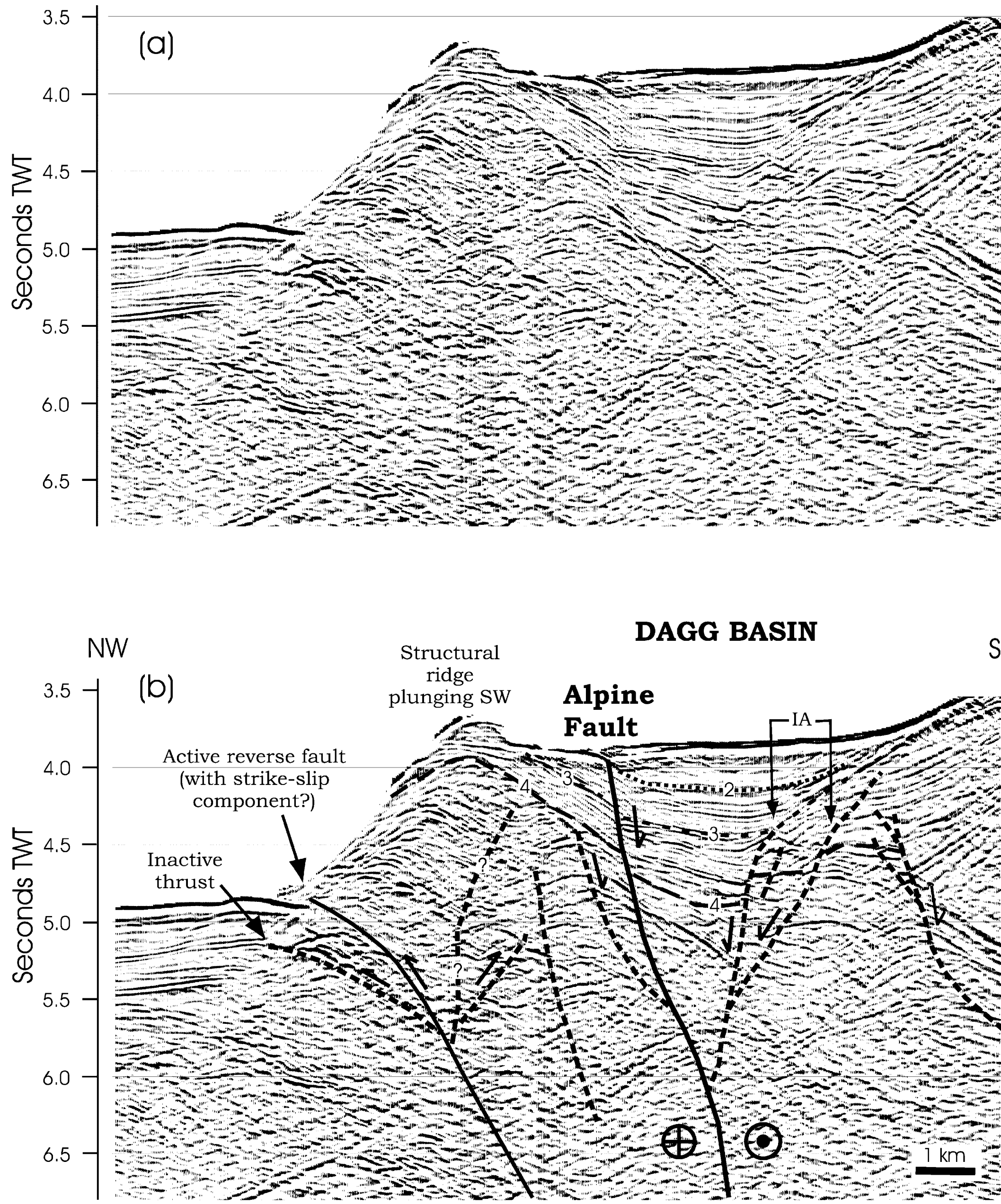

Fig. 5. Uninterpreted (a) and interpreted (b) migrated seismic reflection profile B across Dagg Basin, and the structural ridge to seaward. The location of the profile is shown on Fig. 3. Numbers labelling reflectors and faults are referred to in the text. Dashed faults are inactive. The profile (P3) is a 40-fold section acquired on R/V *Maurice Ewing*. Vertical exaggeration of the profile is 2.2:1 at a velocity of 2 km/s.

12.5 m (typically 10 active channels were recorded), and seismograph recording to 10 s (two-way travel time) at 2 ms sampling rate. Processing included FD and FK filtering, static corrections, spherical divergence, normal moveout correction, deconvolution, and post-stack time migration. These low-fold, high-resolution profiles image up to 2 s (two-way travel) of subsurface section beneath the basin. The profiles are complemented by a 40-fold seismic reflection profile acquired in 1996 on R/V *Maurice Ewing* (Wood et al., 2000). This profile images strong, coherent subsurface reflectivity with up to 4 s penetration. The multichannel seismic data are complemented with 3.5 kHz profiles of the near-surface (<100 ms) sediments.

The EM12D multibeam swath bathymetry and backscatter sonar images of the basin were acquired in 1993 as part of the GeodyNZ-Sud cruise of R/V *L'Atalante* (Collot et al., 1994; Delteil et al., 1996a, 1996b).

4. Structure and stratigraphy of Dagg Basin

Dagg Basin lies beneath the middle to lower continental

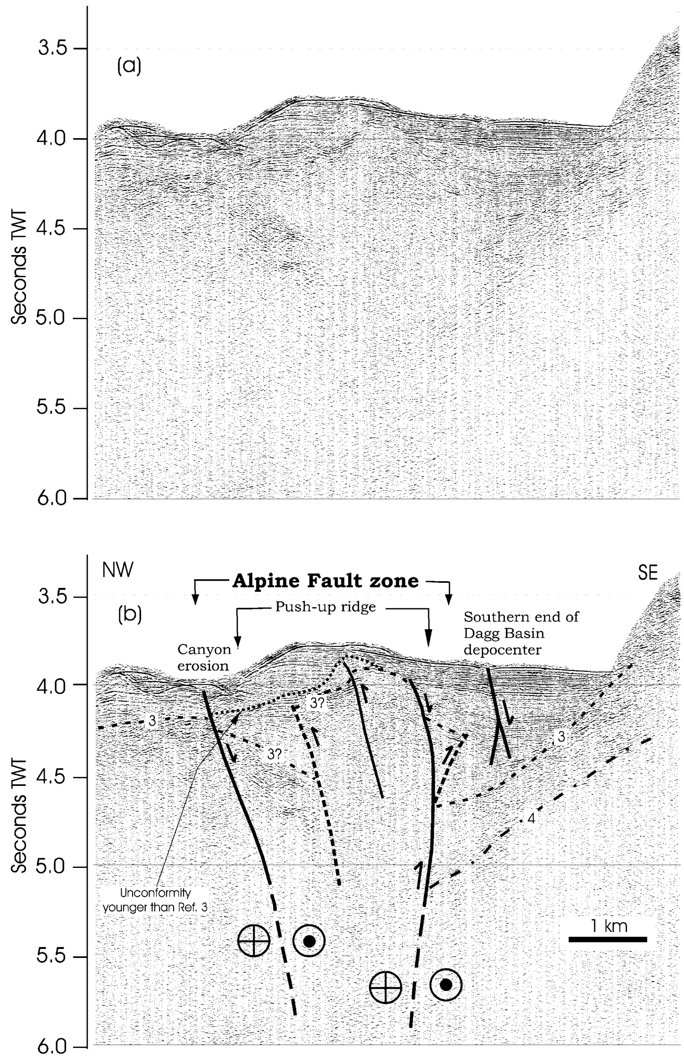

Fig. 6. Uninterpreted (a) and interpreted (b) migrated seismic reflection profile C across the uplifted southern half of Dagg Basin. The location of the profile is shown on Fig. 3. Numbers labelling reflectors and faults are referred to in the text. Dashed faults are inactive. The profile (TA-39) was acquired on R/V *Tangaroa*, and is displayed with a vertical exaggeration of 2.2:1 at a velocity of 2 km/s.

slope, in almost 3000 m water depth, and about 15 km from shore (Figs. 1(b) and 3). The northern half of the basin is 4.5 km wide, and lies between a southwestward-plunging structural ridge and the steep, upper continental slope (Figs. 4 and 5). The northwestern margin of the ridge is characterised by a steep scarp that was inferred by Delteil et al. (1996a, 1996b) to have developed during a previous phase of strike-slip deformation on the margin. Profiles A and B show that the ridge and scarp are underlain by a seaward-vergent reverse (or possibly convergent strike-slip) fault emerging 4–5 km west of the active trace of the Alpine Fault (Figs. 3–5). Inactive faults relating to a previous phase of margin deformation are buried within the ridge.

The strata in Dagg Basin thin toward the crest of the ridge as well as toward Fiordland (Figs. 4 and 5). Four unconformities are recognised within the basin section. These include: surfaces 1 and 2, recognised with confidence only in the northern part of the basin; the widely traceable surface 3; and an older erosion surface labelled 4,which is observed mainly east of the Alpine Fault. The stratal relationships associated with unconformities 1 and 2 are subtle, with reflectors locally eroded by surface 1, and onlapping onto surface 2 (Fig. 4). In contrast, surface 3 is a prominent erosion surface, buried by onlapping sediments, and is recognised throughout the basin. No samples are available to date the strata.

The sediments in Dagg Basin are being deformed by the Alpine Fault (Figs. 4 and 5). The average strike of the fault over a 60 km section northeast of the basin is 040° (Fig. 1(b)). This part of the fault lies typically in 2000–2800 m water depth and is predominantly downthrown to the east, resulting in a discontinuous landward-facing bathymetric scarp up to 180 m high. Where the fault enters the northern region of Dagg Basin, the active traces do not bound the entire basin stratigraphy, but instead cut across the basin,

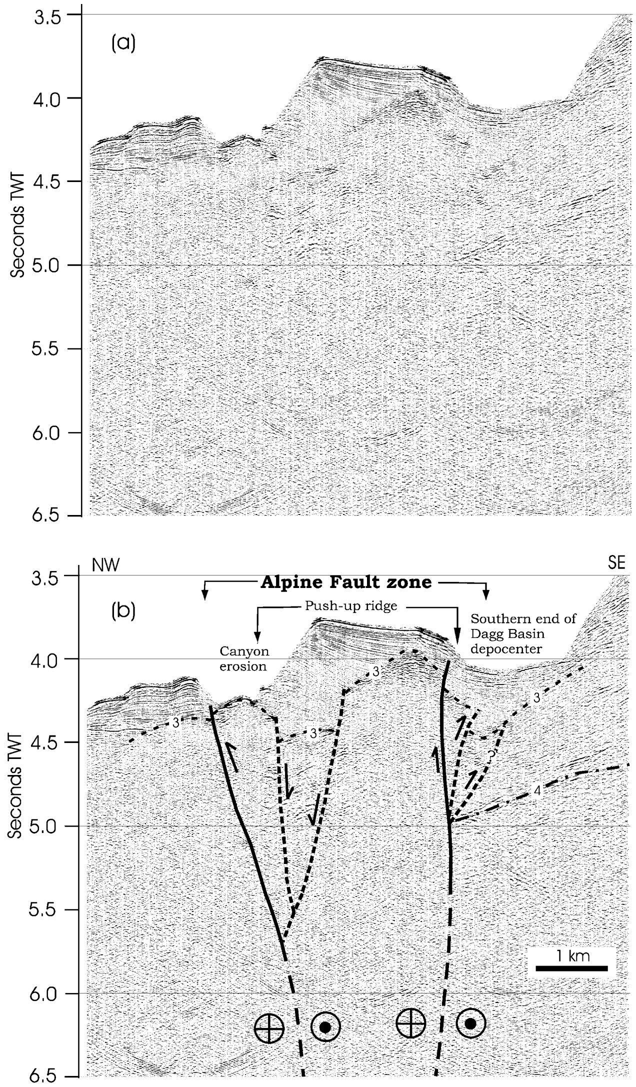

Fig. 7. Uninterpreted (a) and interpreted (b) migrated seismic reflection profile D across uplifted southern half of Dagg Basin. The location of the profile is shown on Fig. 3. Numbers labelling reflectors and faults are referred to in the text. Dashed faults are inactive. The profile (TA-10) was acquired on R/V *Tangaroa*, and is displayed with a vertical exaggeration of 2.2:1 at a velocity of 2 km/s.

displacing the upper part of the sedimentary section and the seafloor (Figs. 3 and 4). The main fault trace continues without interruption through a smooth bend that presently controls the localised area of tectonic subsidence immediately to the south (i.e. the geomorphic basin, stippled on Fig. 3). South of the bend the main trace returns to an average strike of 040° (Figs. 3 and 5).

Across the bend in the Alpine Fault at the northern end of the basin, the fault splays upward into at least five traces with normal separation, two of which vertically offset the seafloor by up to 250 m (Fig. 4). The three eastern splays were active contemporaneously with the latest phase of basin sedimentation, and unconformity 3 is offset with cumulative normal separation of about 0.5 s TWT (two-way travel) (c. 450–600 m, assuming V_{int}~1.8–2.4 km/s). At the southern end of the bend (Figs. 3 and 5, profile B), a single, active, normal-separation fault disrupts the western side of the basin fill, down-throwing sediment to the east.

The seismic profiles show no evidence of active faulting along the eastern edge of the basin (as was inferred by Lebrun et al., 2000). Westward dipping, 020°-striking faults that diverge from the active traces at the northern end of the basin are inactive (Figs. 3–5; faults labelled IA), and are not responsible for the change in surface slope along the eastern edge of the basin.

In contrast to the active subsidence in the northern part of Dagg Basin, most of the southern half of the basin has been uplifted into a lenticular, 14 km long by 3 km wide ridge that plunges and tapers to the northeast and southwest (Figs. 3, 6 and 7). The crest of the ridge lies up to 200 m shallower than the constricted southern end of the basin's present depocenter, which is situated to landward (Geomorphic basin stippled in Fig. 3). The basin stratigraphy is being inverted beneath the ridge, with unconformity 3 offset vertically by up to 0.73 s TWT (c. 660–870 m) by reverse- and normal-separation faults (Figs. 6–8(a)).

The active trace of the Alpine Fault in profile B (Fig. 5) continues southward as the western fault in profiles C and D, where it is eroded by the heads of small, lower-slope submarine canyons (Figs. 3, 6 and 7). About 2.5 km east of this trace on profile C (Fig. 6), a major fault beneath the subdued northeastern side of the ridge is buried by the youngest (upper 0.1–0.3 s TWT) sediments in the basin. This fault continues farther south beneath the eastern side of the ridge, where it deforms the seafloor and clearly controls the uplift of the ridge (Fig. 7). The youngest strata beneath the ridge are tilted towards Fiordland.

The combined bathymetry and seismic data indicate that the eastern fault is curved, with strike of about 015° in the north and 055° in the south (Fig. 3). The southern end of the fault does not appear to extend into Breaksea Basin south of the ridge. We infer that in cross section the fault probably merges with the main (western) trace of the Alpine Fault at a depth of about 3–4 km.

To the south of the ridge the main trace of the Alpine Fault continues with strike of 040° along the western boundary of Breaksea Basin (Fig. 3). There, a landward-facing scarp that is breached by a canyon ranges from about 50–200 m in height, comparable to that north of Dagg Basin.

5. A strike-slip basin: northern development at a releasing bend, southern inversion under transpression

The Alpine Fault is well expressed in the tectonic geomorphology of the margin, and can be traced with confidence from northern Fiordland to south of Dagg Basin (Fig. 1(b)). Although there are no direct marine observations of laterally-offset piercing points, the structural style along the fault zone, interpreted by Lebrun et al. (2000), including lobate basins positioned at fault stepovers, lens-shaped

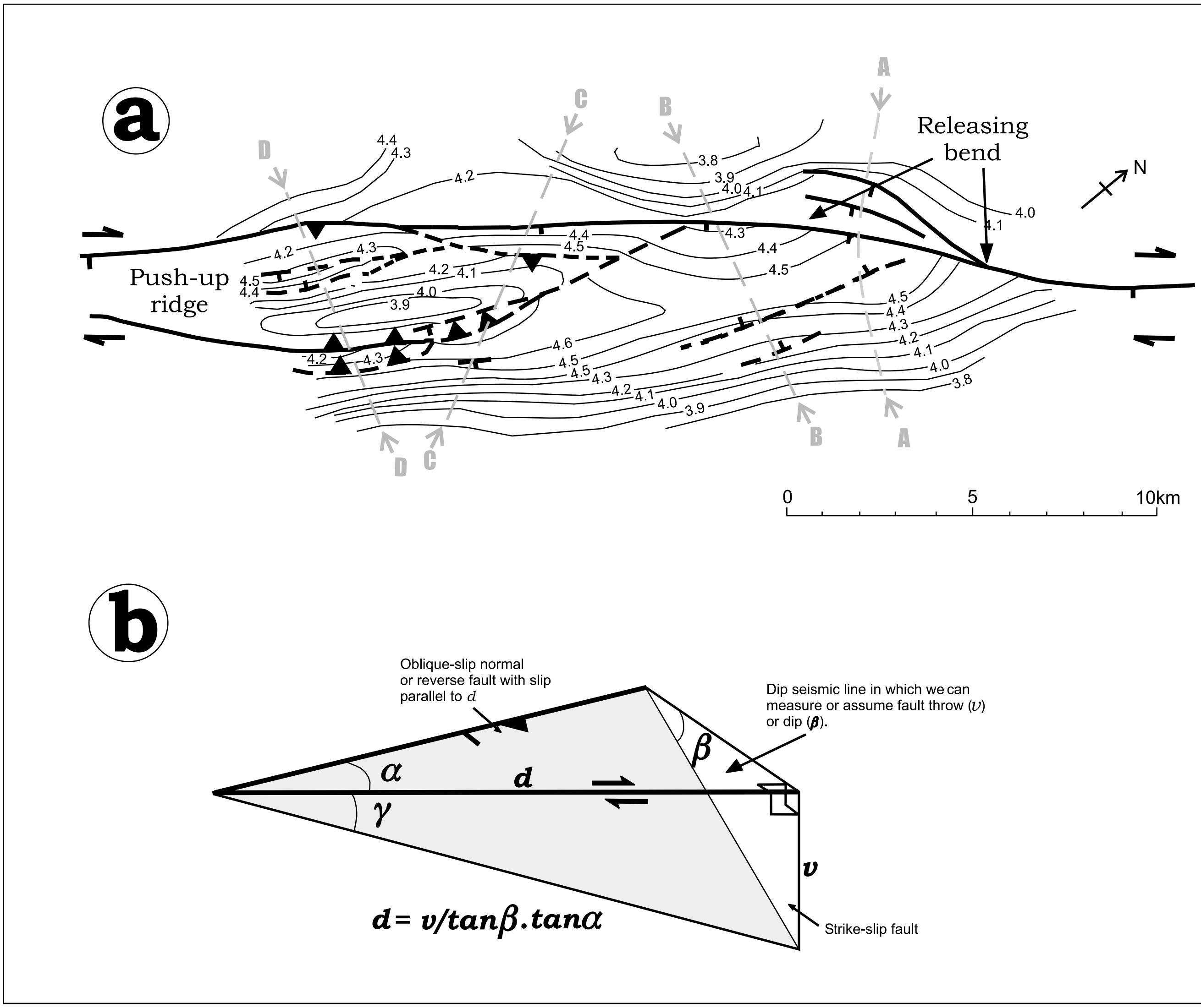

Fig. 8. (a) Structure contour (in seconds TWT) on the late Pleistocene surface 3 imaged in seismic profiles A–D (Figs. 4–7). (b) Simple geometrical model for estimating the component of lateral motion required to produce the observed vertical separation on the oblique slip structures at the releasing bend and in the push-up sliver.

tectonic ridges aligned en echelon, and anastomosing fault traces, are consistent with strike-slip deformation along the length of the fault (e.g. Christie-Blick and Biddle, 1985; Sylvester, 1988). Such deformation is consistent with dextral displacements observed on land (Norris et al., 1990; Berryman et al., 1992; Sutherland and Norris, 1995), and with alignment of the fault within 25° of the azimuth of the Pacific–Australian plate motion vector (Fig. 1(b)).

Based on (1) the patterns of earthquake ruptures associated with strike-slip faults (e.g. Tchalenko and Ambraseys, 1970; Sibson, 1986; Deng et al., 1987; Zachariasen and Sieh, 1995), (2) field structures observed in strike-slip basins (e.g. Freund, 1971; Mann et al., 1983; Christie-Blick and Biddle, 1985; Wood et al., 1994; Reijs and McClay, 1998), and (3) the results of laboratory analogue experiments (e.g. Dooley and McClay, 1997; Basile and Brun, 1999), we interpret the structure of Dagg Basin to be the result of strike-slip displacement associated with a 3 km-wide stepover on the Alpine Fault. In the region of the stepover, the active surface trace is a smooth, continuous releasing bend, with no evidence at the surface for overlapping segments developing. Sag depressions associated with the subsiding depocentre are located against, and immediately south of, the releasing bend (Fig. 3), which is consistent with dextral displacement on the fault.

Upward splaying normal-separation faults within the region of the releasing bend are inferred to distribute oblique extension across a 2 km wide zone north of the main trace (Figs. 3 and 4, profile A). These faults resemble the early stages of the development of extensional sidewall structures that have been observed in some sandbox experiments (Dooley and McClay, 1997) and field examples of pull-apart basins (Reijs and McClay, 1998). In contrast to

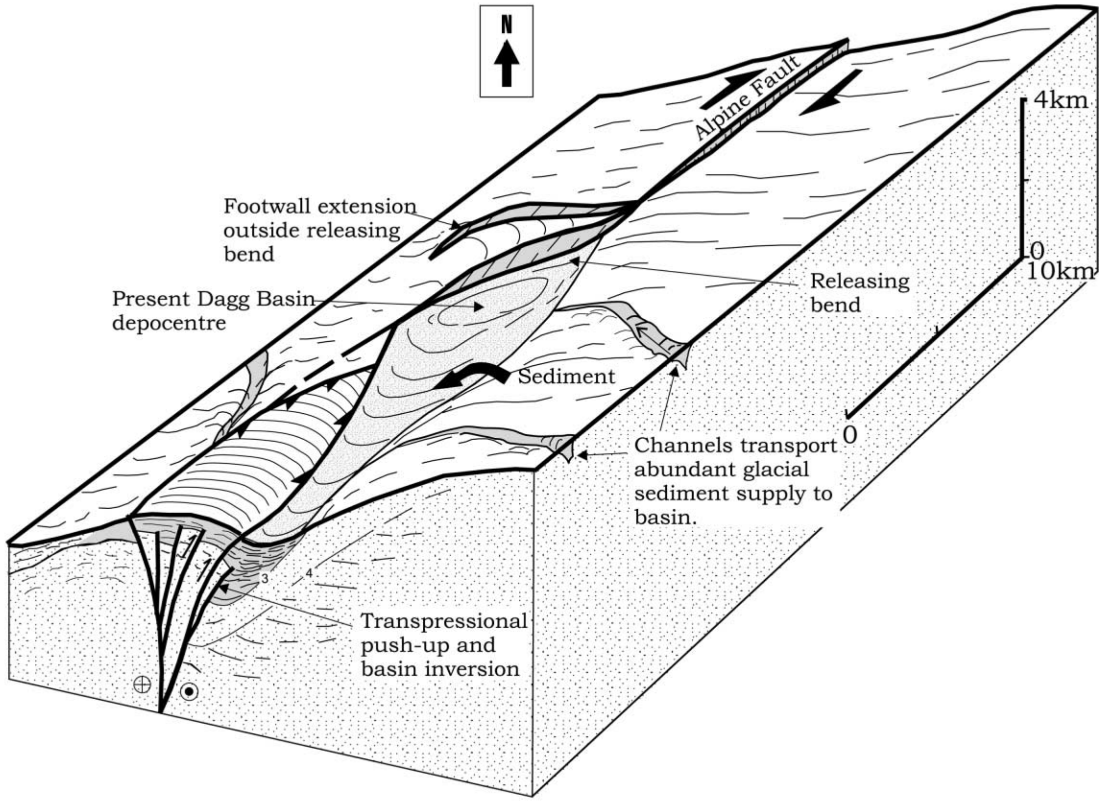

Fig. 9. Schematic block diagram (not to scale) of Dagg Basin releasing bend and tectonic push-up structure.

sandbox experiments, however, the active extension in Dagg Basin is asymmetric, being accommodated entirely by oblique-slip displacement on southeast-dipping faults across the releasing bend, with no evidence for active faulting along the eastern margin of the basin. The surficial structural geometry resembles other basins that have been interpreted to represent an incipient stage of pull-apart basin development (Mann et al., 1983).

Despite the relatively simple structure of the present surface traces, growth strata adjacent to faults show that between development of unconformities 3 and 4, opposite dipping faults, including the active trace and faults labelled IA, were active contemporaneously and bounded a graben in the centre of the basin (Fig. 5). In profile B the west dipping faults were active until surface 3 developed, and in profile A they were active almost until surface 1 developed. This is suggestive that prior to unconformity 3, the structure of the stepover region may have been more complex than at present, and a pull-apart basin may have existed between separate segments of the Alpine Fault, behind the growing structural ridge to seaward. The stratigraphic relationships in profile A (Fig. 4) indicate that the through-going surface trace at the releasing bend developed mainly after unconformity 3, and cut across the basin fill. In this respect, the through-going trace at the releasing bend has some similarities to cross-basin faults that have been modelled (Dooley and McClay, 1997), and observed in earthquake ruptures (Deng et al., 1987; Zhang et al., 1989), in mature pull-apart basins. Thus, Dagg Basin is interpreted to be a hybrid case where a pull-apart basin developed at a stepover in the Alpine Fault, behind a growing reverse-faulted ridge at the rear of the accretionary wedge, and later evolved into a more simple releasing bend on the principal displacement fault zone.

In contrast to the subsidence and extension of northern Dagg Basin, the southern half is characterised by uplifted and inversion of basin strata (Figs. 3, 6, 7 and 8(a)). We interpret the lenticular, 14 km-long by 3 km-wide ridge as a strike-slip push-up (Crowell, 1974) resulting from transpression. The ridge is inferred to be a tectonic sliver that is being squeezed upwards between the main trace of the Alpine Fault on the west, and the curved, reverse-separation (and probably oblique-slip) fault beneath its eastern margin (Fig. 9). Profiles C and D (Figs. 6 and 7) reveal substantial reverse-separation of surface 3, as well as monoclinic folding and fault displacement of the post-surface 3 growth strata deposited during deformation. Anticlinal folding typical of the accretionary wedge to the west of the basin (Figs. 1 and 2) is absent from within the ridge because the uplift is being driven largely by displacements that are out-of-the-plane of the profiles.

The coexistence of extensional and contractional structures along major strike-slip faults is a common occurrence at a plate boundary scale (e.g. Christie-Blick and Biddle, 1985; Harding, 1990; Calais and Mercier de Lépinay, 1991; Barnes and Audru, 1999), but is less common at the scale of individual strike-slip basins. One geometrically analogous example with similarities to Dagg Basin is the 20 km-long onshore Hamner Basin on the strike-slip Hope Fault, northern South Island, New Zealand (Fig. 1(a)) (Freund, 1971; Wood et al., 1994). This c. 1 Myr old basin is forming where a 6–7 km-wide releasing stepover is linked by an oblique-slip transfer fault, and is being inverted at the other end as a result of convergence in azimuth of the two principal displacement faults. This inversion mechanism differs from Dagg Basin, where the immediate strike of the Alpine Fault is parallel on either side of the releasing bend, and where the inversion structure is a wedge of sediment that is being pushed up between the main fault trace and an arcuate splay that disrupts the basin fill.

6. Glacial sedimentation, and the age of onlap surface 3

We can infer the age of the sediments above surface 3 by considering regional sediment supply and depositional responses to the major climatic cycles that have effected the margin. The steep continental slope east of Dagg Basin shoals directly into coastal mountains consisting of crystalline metamorphic rocks deeply dissected by fiords (Figs. 1(b) and 2). There is no continental shelf on the upper margin. Despite present orographic rainfall of >6 m/yr, the rate of terrigenous sedimentation in the fiords during the Holocene, and presumably during previous interglacial times, is low (<1 m/kyr) due to dense vegetation cover on resistant basement rocks, and an absence of glaciers in the head valleys (Pickrill, 1987; Suggate, 1990). These organic-rich interglacial sediments are trapped in the fiords behind coastal sills, and are not available to the offshore margin. In contrast, during glacial ages major valley glaciers filled and eroded the fiords. During these times, forest vegetation was stripped and erosion rates from glacial processes were very much higher than present day (Pickrill et al., 1992). At maximum glacial advance, major valley glaciers reached the open coast, probably as grounded tidewater glacial fronts providing voluminous mud, sand, and gravel via a range of processes directly to the continental slope (e.g., Powell and Molnia, 1989). This is evidenced by (1) wide slope fan apron and channel-fill sequences of clastic sediments that exhibit high back-scatter sonar intensity on EM12D imagery (Fig. 1); and (2) abundant glacial boulders and cobbles of Fiordland origin recovered in dredge samples from the margin in >1000 m water depths. At least six submarine canyons funnelled mass flows from coastal glacier termini into Dagg Basin (Fig. 3). At a first order, therefore, the continental slope sedimentation cycle reflects a switch on with large sediment flux in peak glacial times, and a switch off in interglacial times.

Seismic surface 3 is the youngest regionally extensive unconformity in Dagg Basin. Burial and onlap on this surface commenced after a period of erosion and non-deposition, and with the onset of a major flood of glacier-derived terrigenous sedimentation into the basin. This sedimentation pulse is likely to have coincided with maximum, or near maximum, glacial advance, when tidewater glaciers would have grounded near the coast. The preceding period of erosion and non-deposition represented by surface 3 probably occurred during interglacial or interstadial times. The last major ice advance occurred during the last glacial period (Suggate, 1990). We interpret the youngest possible age for the inception of development of onlap on surface 3 to be about 24 ka, at the transition from the last glacial interstadial to the last glacial maximum (corresponding to the oxygen isotope stage 3—2 boundary) (Imbrie et al., 1984). Two other possible ages are: (1) 71 ka, the onset of the last glacial stadial (oxygen isotope stage 5—4 boundary); and (2) 110 ka, the significant cooling event at the oxygen isotope stage 5d—5e boundary.

7. Recent Alpine Fault displacements and slip rates

7.1. Estimates of recent dextral displacement

If we assume that bulk displacement is parallel to the main 040°-striking traces of the Alpine Fault, and that oblique slip at the releasing bend accommodates all of the active extension at the northern end of the basin, then we can estimate approximately the dextral strike-slip component required to produce the observed normal-separation of 450–600 m on surface 3 in profiles A and B (Figs. 4 and 5). Simplifying the shallow parts of the faults as planar surfaces,

$$d = v/(\tan\beta . \tan\alpha)$$

where d is the displacement parallel to the bulk displacement, v is the throw on the oblique-slip fault, β is the dip on the oblique-slip fault perpendicular to regional fault strike (i.e. approximately within the plane of the seismic profiles), and α is the angle of obliquity between the oblique-slip fault and the direction of bulk displacement (Fig. 8(b)). If it is assumed that 060°-striking faults in the releasing bend have an average dip in the range of 45–70°, then dextral displacement of the order of 450–1650 m has occurred across the releasing bend since the formation of onlap surface 3. Although the 3-dimensional geometry of the structures appears more complex than simple, planar surfaces, we consider this will not undermine the usefulness of these estimates at a first order.

Using the same method, we can estimate the dextral strike-slip component of displacement required to produce the observed reverse-slip separation offset of surface 3 within the transpressive push-up sliver. If we simplify the dominant 015°-striking oblique-slip reverse fault on the northeastern edge of the push-up as a planar surface dipping west at $70 \pm 10°$ and merging with the main trace at depth, then the vertical separation of surface 3 of 660–880 m in

Table 1
Dextral slip rate estimates for three possible ages of onlap surface 3, across the releasing bend on the Alpine Fault at the northern end of Dagg Basin. The plate motion rate of 35 ± 3 mm/yr constrains the upper limit of the actual slip rate

Age of onlap surface 3 (ka)	Post-surface 3 dextral displacement of 450–1650 m (mm/yr)
24	19–69
71	6–23
110	4–15

profiles C and D (Figs. 6 and 7) results from dextral displacement of the order of 250–1085 m.

7.2. Late Quaternary dextral slip rate

Our structural data enable the first estimations to be made of the dextral slip rate on the offshore part of the Alpine Fault. If we assume from above that (1) surface 3 commenced forming between 110 and 24 ka ago, and (2) that post-surface 3 dextral displacement at the releasing bend on the fault is of the order of 450–1650 m, then a range of possible dextral slip rate of the order of 4–69 mm/yr is implied at Dagg Basin (Table 1). An upper constraint on the actual slip rate is the total Pacific–Australian plate oblique convergence rate of 35 mm/yr, about 32 mm/yr of which can be resolved parallel to the plate boundary (Fig. 1(b)). Although poorly constrained, the slip rate can be tested with future research. A slip rate of 26 ± 6 mm/yr was determined on the Alpine Fault onshore about 140 km to the northeast (Sutherland and Norris, 1995). If this rate continues southward to Dagg Basin, the age of surface 3 should be of the order of 14–82 ka. This is consistent with the analysis presented above.

8. Implications for the growth and longevity of strike-slip basins

The marine seismic profiles and multibeam bathymetry presented in this paper reveal important insights into the 3-dimensional structure and recent evolution of the southern part of the Alpine Fault and its sedimentary basins. Many experimental studies have simulated the development of strike-slip faults to study the evolution of Reidel (R), Y, and P shears, en echelon folds, and the growth of the principal displacement zone with increasing total displacement (e.g. Wilcox et al., 1973; Richard and Cobbold, 1990; Richard et al., 1995; Dooley and McClay, 1997; Basile and Brun, 1999). In some field examples, some theoretically-predicted shear fractures have been identified as surface ruptures in Holocene sediments following large magnitude strike-slip earthquakes (e.g. Ringenbach et al., 1992). Considering the long history (c. 15–20 Myr) of strike-slip deformation on or near the Alpine Fault, the very large (480 km) total dextral displacement revealed by offset of basement terranes in the South Island, and the influence of pre-existing structures in the development of the fault (Delteil et al., 1996a, 1996b; Lebrun, 1997; Wood et al., 2000; Sutherland et al., 2000), one might expect the structure of the fault to depart somewhat from theoretical models of faulting under simple shear (Christie-Blick and Biddle, 1985; Sylvester, 1988).

Two important observations in Dagg Basin have generic implications for the temporal and spatial evolution of structures and sedimentary basins on mature continental strike-slip faults. Firstly, the seismic profiles show that the prominent tectonic geomorphology associated with the releasing bend and push-up sliver developed very recently (mainly <110 kyr) in the history of the Alpine Fault. The major strike- and oblique-slip structures controlling the present geomorphology therefore reflect only the latest phase in the evolution of the fault. Prior to this phase a more complex, late Pleistocene pull-apart basin may have existed at the rear of the accretionary wedge. Secondly, the profiles reveal a very rapid spatial evolution of surface faulting in late Quaternary strata within the Alpine Fault zone. Numerous upward-branching splays imaged both within the tectonic push-up and subsiding basin displace surface 3, but few exhibit stratigraphic growth in the youngest surface sediments and few reach the seabed as prominent scarps. We speculate that this rapid spatial evolution of surface faulting may be facilitated by the interactions between high fault slip rate, voluminous but episodic Pleistocene glacial sediment supply, inherited structural complexities in the basement rocks and deeper cover sequence, and complex interactions between the Alpine Fault and adjacent faults.

Together, our observations provide an excellent example of the rate at which strike-slip basins and associated structural complexities can develop on a major through-going fault with high displacement rate, a long growth history, and large total displacement. These data support observations in China by Sibson (1986) and Zhang et al. (1989), which suggest that strike-slip basins and associated structures on such faults can be ephemeral features that can be developed and destroyed on a timescale of 10^5–10^6 years.

9. Conclusions

1. This paper integrates interpretations of four seismic reflection profiles with multibeam bathymetry and back-scatter imagery data to analyse the structure of the 25 × 4 km strike-slip Dagg Basin, offshore Alpine Fault, southern New Zealand. Firstly, the results support a regional tectonic model that the Alpine Fault continues as a major through-going continental structure along the length of the Fiordland margin. Secondly, the results have implications for the rates at which structural complexities and sedimentary basins can develop within highly active, fully mature, continental wrench faults.

2. The northern half of the basin is currently developing in almost 3000 m water depth at a through-going releasing bend on the Alpine Fault. Basin subsidence is not presently controlled by stepover between separate segments of the principal displacement zone, but such segmentation may have existed previously in the late Pleistocene. Instead, active subsidence is accommodated by oblique extension on a smooth, continuous fault trace through the releasing bend, which exhibits a step-over width of about 3 km. Footwall collapse across the releasing bend distributes the extensional deformation over a 2 km wide zone.
3. The southern half of the basin is being uplifted and inverted into an elongate tectonic push-up that results from squeezing a faulted sliver of the basin fill between the main trace of the fault on the west and an oblique-slip splay to the east.
4. Significant basin sedimentation is restricted to periods of glaciation when glaciers filled and eroded coastal fiords 15 km to the east. During the last glaciation, Dagg Basin and the surrounding margin were flooded by glacio-marine clastic sediments inferred to have been derived from grounded tidewater glacial fronts at the mouths of fiords. With no continental shelf on the margin, the glacial sediment was directly available for mass transport to tectonic basins on the slope. We infer that at present the basin is not actively infilling.
5. Simplifying the geometries of the major basin structures enables an estimation of dextral displacement and slip rate since the development of a prominent unconformity estimated to be between 24 and 110 ka old. Estimates of 450–1650 m dextral displacement across the releasing bend imply a range of possible dextral slip rates from a minimum of 4 mm/yr to the maximum of 35 mm/yr constrained by the Pacific–Australian plate motion rate.
6. Despite total dextral displacement of 480 km on the Alpine Fault and a fault growth history of 15–20 Myr, the present tectonic geomorphology of the basin developed mainly within the last 110 kyr. Within this period, upward splaying structures within the Alpine Fault zone exhibit a rapid spatial evolution that may reflect the interactions between high fault slip rate, voluminous but episodic sedimentation supply, inherited structural complexities in the basement rocks and deeper cover sequence, and interactions between adjacent faults.
7. Strike slip basins on the scale of 40–80 km^2 on mature continental faults may be ephemeral features that can be developed and destroyed during plate boundary evolution, on a time scale of 10^5–10^6 years.

Acknowledgements

The crew and officers of R/V *Maurice Ewing* and *Tangaroa* are thanked for help with data acquisition. Ray Wood and Anne Melhuish processed and provided us with the *M. Ewing* profile data. Jarg Pettinga provided helpful advice with the structural analysis. The manuscript was greatly improved by helpful comments from Jarg Pettinga and Geoffroy Lamarche, from journal reviewers Mike Hall and Chris Goldfinger, and from Associate Editor, Richard Norris. The New Zealand authors thank the Foundation for Research Science and Technology for funding of contracts CO1624 and CO5811. Jean Delteil thanks UMR Géosciences Azur and Ministère des Affaires Étrangères Français for travel costs to New Zealand.

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