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Cenozoic Strike-Slip Induced Basin Inversion in the Ross Sea, Antarctica

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Abstract - Tectonic analysis of the ANTOSTRAT seismic reflection data set has allowed us to identify compressional deformations affecting the sedimentary infill of some Mesozoic-Cenozoic basins in the Ross Sea, Antarctica. Inversion tectonics is always younger than the unconformity RSU6 (about 30 Ma) and affects basin-controlling faults belonging to the two NW-SE and N-S major fault trends in the Ross Sea. A few NE-SW trending basins have also been found in the Iselin Bank area and in the southern Central Trough. The structural style of inversion is different in the NE-SW faults with respect to the NW-SE and N-S. In the pre-RSU-6 NE-SW trending tectonic depressions (Iselin Bank area and southern Central Trough) inversion affects mainly the border faults and all the sedimentary sequence is concordantly deformed. Contractional deformation in the NW-SE trending tectonic depressions is well localized and frequently occurs in the central region, associated with steeply dipping faults. The overall geometries closely resemble positive flower structures. Positive flower structures also occur along some N-S faults, particularly in the Victoria Land Basin, where they are also associated to magmatic intrusions. The contemporary occurrence of positive inversions along NE-SW trending faults and oblique slip or strike-slip related inversions along NW-SE and N-S faults well fits in an overall framework of Cenozoic regional, right-lateral strike-slip tectonics along the NW-SE major fault zones in the Ross Sea Region. Positive inversion of NW-SE and N-S extensional faults relates to the kinematics (*sensu* Davis, 1984) of relative motions between fault blocks and has been defined as kinematic inversion. On the other hand, positive inversion of NE-SW extensional faults is produced by the stress field in the regions adjacent to major right-lateral strike-slip belts and has been defined as dynamic inversion (*sensu* Davis, 1984).

INTRODUCTION

The tectonic framework of the Ross Sea Region, namely the area including the Victoria Land north of Ross Island and the Ross Sea (Fig. 1), is derived from a long-lived complex evolutionary path that can be divided into three main periods: an initial one (105-85 Ma) of lithosphere thinning and continental break-up (Cooper et al., 1987; Tessensohn & Worner, 1991; Lawver & Gahagan, 1994); a second period (starting at about 55 Ma) characterized mainly by higher subsidence rates, lower amounts of overall extension and magmatic activity (Cooper et al., 1987; Tessensohn & Worner, 1991; Lawver & Gahagan, 1994); a third evolutionary period (30 Ma to present) during which extensional deformation is being overprinted by a transtensional kinematics (Salvini et al., 1997a). This transtension results from the right-lateral strike-slip tectonics along NW-SE trending fault zones that has being affecting the Ross Sea Region during the Cenozoic (Brancolini & Salvini, 1994; Salvini et al., 1997b). Compressional deformations have been identified within this transtensional framework, mostly as re-activations of pre-existing extensional faults.

The reversal of motion along basin-controlling extensional faults during compressional deformation has been defined as positive inversion by Williams et al. (1989). In this paper we describe different styles of positive basin inversion in the Ross Sea and we show how these differences can be related to the relative orientation between the re-activated faults and the regional strike-slip belts.

GEOLOGICAL FRAMEWORK

The sedimentary succession of the Ross Sea is made up by eight seismic sequences, from the bottom to the top RSS-1 to RSS-8, separated by seven major unconformities, from the bottom to the top RSU-6 to RSU-1 (see ANTOSTRAT, 1995) (Fig. 2). The age of the base of RSS-1, *i.e.* the age of the opening of the Ross Sea, is still unknown while unconformity RSU-6 can be inferred to be about 30 Ma old (Busetti, 1994). RSU-6 can be used as a reference layer to separate transtensional deformations, that postdate this unconformity (post RSU-6; 30 Ma to present), from the older extension (pre RSU-6; 105-30 Ma).

The overall tectonic architecture of the Ross Sea consists of four major pre-RSU-6 depocenters, namely the Victoria Land Basin, the Northern Basin, the Central Trough and the Eastern Basin, and of two major intrabasinal highs, the Coulman High and the Central High (Cooper et al., 1987) (Fig. 1). The mean orientation of these basins is roughly N-S, as well as many other smaller depocenters. Some pre-RSU6 small basins in the Northern Basin-Coulman High area trend meanly NW-SE and a few small basins south of the Iselin Bank and in the southern Central Trough trend NE-SW.

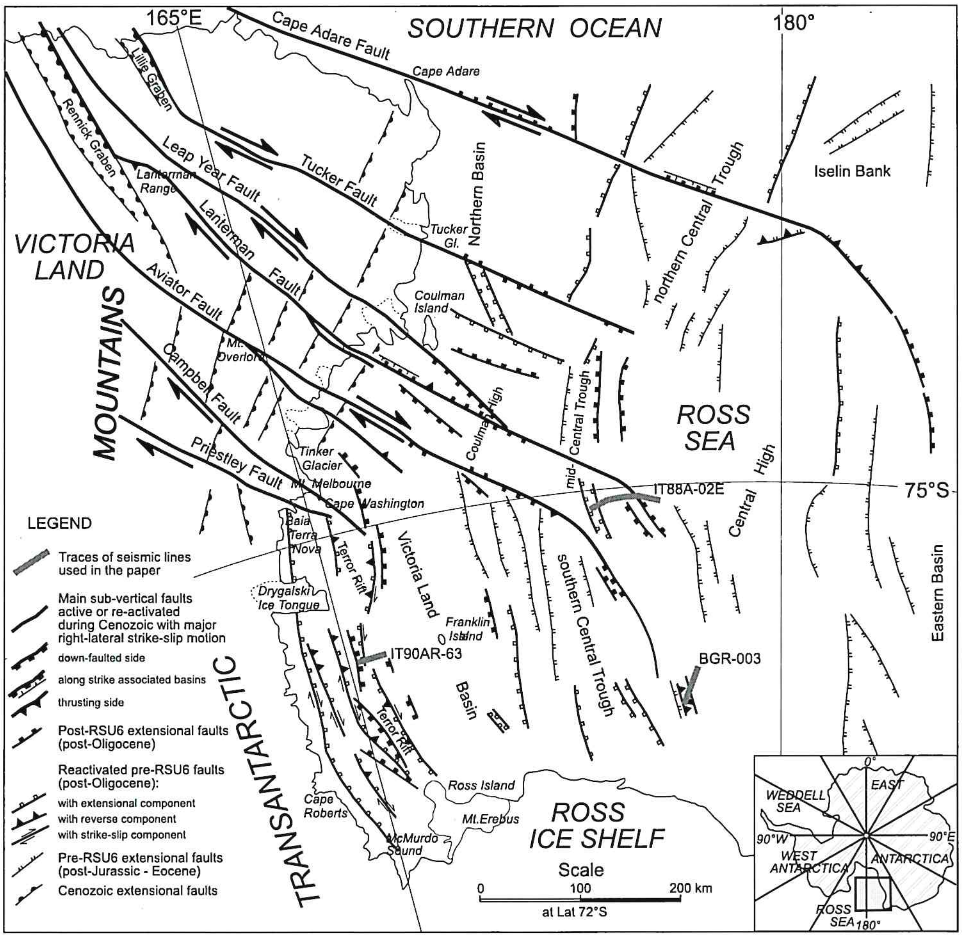

Fig. 1 - Tectonic map of the Ross Sea Region (simplified from Salvini et al., 1997a). Locations of the seismic lines of figures 5, 6, and 8 are shown.

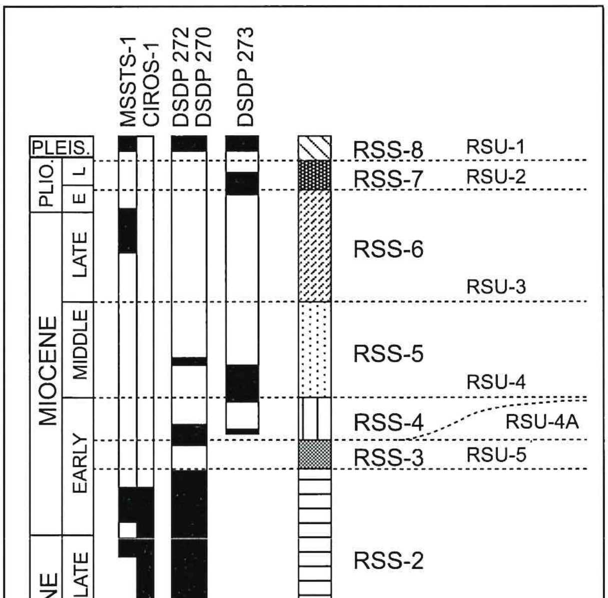

Fig. 2 - Scheme of the eight major seismic sequences that have been defined in the stratigraphic succession of the Ross Sea.

During the last 30 Ma the evolution of the Ross Sea Region has been dominated by a regional right-lateral strike-slip tectonics along major NW-SE trending deformation belts that can be traced from the northern coast of Victoria Land, to the Central High in the Ross Sea (Salvini et al., 1997a; Rossetti & Storti, 1997, unpublished data). The activity of these Cenozoic strike-slip belts has been triggered by relative movements among the Antarctica, Australia and New Zealand plates (Salvini et al., 1997a).

The pre RSU-6 tectonic framework of the Ross Sea Region is characterized by NW-SE trending fault zones, most of which generated during the Cambrian-Ordovician Ross Orogeny (*e.g.* Kleinschmidt & Tessensohn, 1987) as major transpressional belts and terrane boundary faults (Weaver et al., 1984; Gibson, 1985). The Paleozoic tectonic anisotropy of the crystalline basement of the Ross Sea Region has provided inherited NW-SE regional scale weaker discontinuities that have been re-activated as post RSU-6 right-lateral strike-slip regional faults. In the Ross Sea, the Paleozoic tectonic framework of the crystalline basement has been overprinted by the Mesozoic-Cenozoic pre RSU-6 extensional tectonics along mainly N-S and NW-SE fault trends. In the last 30 Ma, due to the onset of the right-lateral strike-slip kinematics in the whole Ross Sea Region, pre RSU-6 N-S and NW-SE basin-controlling faults in the Ross Sea have reactivated with a normal throw component and a horizontal one, thus providing a suitable mechanism to accomplish for the horizontal displacement associated to the right-lateral strike-slip fault zones (Salvini et al., 1997b). This overall transtensional kinematics has also triggered the volcanic activity in the coastal sector of Victoria Land and along the western shoulder of the Ross Sea, where the bulk rheology of the crust favors a semi-brittle behaviour (Salvini et al., 1997a).

Nevertheless, even in a transtensional regime, some pre-existing and newly-formed basin-controlling faults in the Ross Sea show a post RSU-6 reverse throw component that has produced anticlinal folding in the sedimentary succession, *i.e.* positive basin inversions.

TIMING OF BASIN INVERSION

Generally, compressional deformations affect the stratigraphic succession up to RSS-6 and RSS-7 (Fig. 2). In several cases folding and faulting occur also in the seismic sequence RSS-8. Only in a few cases inversion structures are older than RSU-4. We can thus constrain the time span of the main compressional inversion in the Ross Sea from the Early Miocene to the Pleistocene. Many faults cut through the whole sedimentary succession and have morphological expressions in the sea bottom, thus suggesting that they are probably still active.

In this paper we will regard both the first extensional event in the Ross Sea (105-85 Ma) and the second period of extension (55-30 Ma) as pre RSU-6 faulting, and the subsequent transtension and local positive inversion (30 Ma to present) as post RSU-6 faulting. This paper focuses on the overall kinematics of this phenomenon in the whole region and on its relationships with the strike-slip tectonics, not on the detailed evolution of each of the inverted basins.

MODES OF BASIN INVERSION

The overall transtensional framework in the Ross Sea during the last 30 Ma is characterized by a partitioning of deformation into regional NW-SE strike-slip faulting, interfault extension along N-S trending faults, local extension along NW-SE and N-S fault trends. Local inversion along NW-SE and N-S fault trends and interfault inversion along NE-SW trending faults are also present (Figs. 1 & 3; Salvini et al., 1997a, 1997b). This deformation pattern results from the distribution of the kinematically induced stresses and of the dynamic stresses, and from the geometrical array of inherited fault trends. Different styles characterize the pop-up/positive-flower (Sylvester, 1988) inversion structures that developed along different fault trends. This is particularly true for the NE-SW trending structures with respect to the other two trends (N-S and NW-SE). Differences arise from the relative position of the inverted pre RSU-6 basin-controlling faults with respect to the regional strike-slip fault zones. According to this criterion, three different geometric arrays that have undergone post RSU-6 basin inversion can be recognized in the Ross Sea (Figs. 1 & 3): along strike basins (*i.e.* south east edge of the Lanterman Fault, Fig. 5), en echelon basins (*i.e.* Terror Rift, Fig. 7), and across strike basins (south east edge of the Aviator Fault, Fig. 9). The reactivation according to the latter two types of basins will modify the amount of relative displacement along the related strike-slip fault (Salvini et al., 1997b).

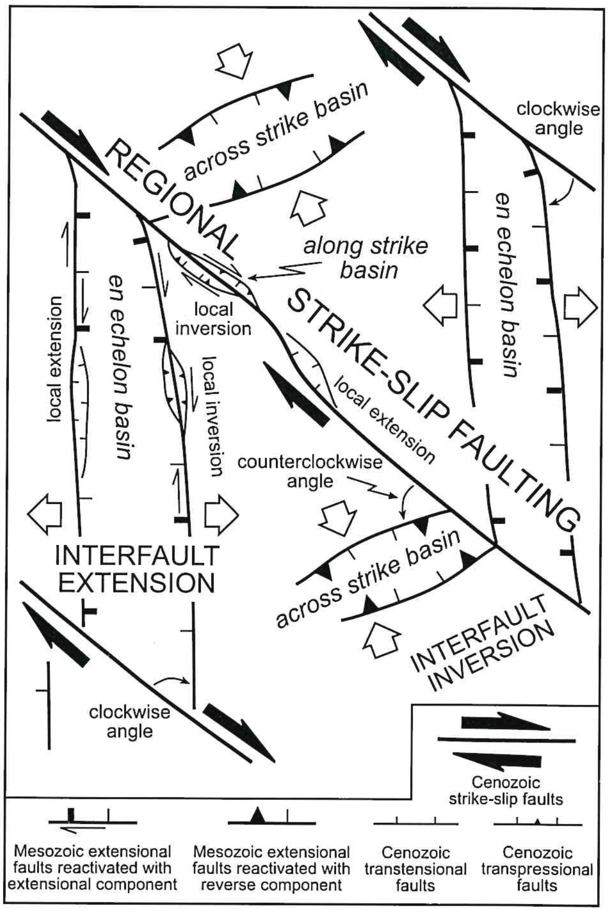

Fig. 3 - Scheme of the geometric relationships between regional right-lateral strike-slip faults and the inverted basins.

ALONG STRIKE BASINS

Basins that are oriented roughly parallel to the post RSU-6 right-lateral strike-slip fault zones are defined along strike basins (Fig. 3). Such basins provide weaker sectors within the thinned continental crust of the Ross Sea, lying along the strike of the post-RSU-6 strike-slip regional faults. This enhances the forward propagation of the strike-slip faults, that eventually may cut across the basins themselves (Fig. 4a, b). Pre RSU-6 extensional faults provide inherited weaker surfaces that may reactivate with a strike-slip kinematics. Displacement is characterized by a major horizontal component and a subordered component of dip-slip throw. In the conceptual cross section of an inverted along strike basin of figure 4b only some of the pre-Miocene extensional faults reactivated as transpressional ones, in a local positive flower structure and probably relate to the presence of slight restaining bends. Localization of deformation in narrow zones is a diagnostic feature of strike-slip tectonics.

An example of positive inversion of an along strike basin is shown in figure 5. Basin opening is recorded in the

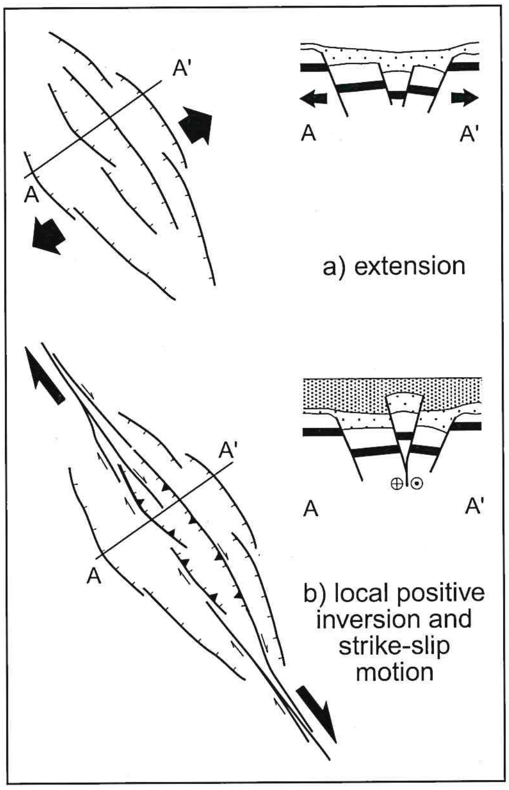

Fig. 4 - Conceptual map view and cross section of an along strike basin. *a)* Pre-inversion extensional basin; *b)* inversion of some basin-controlling faults.

sin-extensional sequence RSS-1. Most of the pre-Miocene extensional faults do not cut across unconformity RSU-6. Only some faults re-activated with a local transpressional kinematics as can be inferred from the overall positive flower geometries of the inversion structure.

EN ECHELON BASINS

Pre RSU-6 basins that have a synthetic en echelon geometric array with respect to the post RSU-6 right-lateral strike-slip fault zones (*i.e.* roughly N-S) are named *en echelon* basins (Fig. 3). En echelon basins lie at a small clockwise angle from the strike-slip master faults and show geometries similar to along-strike basins. In this geometric configuration the weaker crustal sectors provided by the pre RSU-6 basins do not directly favor the forward propagation of the tips of the post RSU-6 strike-slip fault zones. Nevertheless, the often small angle between the en echelon basins and the strike-slip fault zones (about 30°) favors a partial transfer of horizontal motion from the strike-slip faults to the basins themselves, that may undergo even local transpressional deformation within an overall transtensional kinematics. As in the former case, displacement is characterized by a major horizontal component and a subordered dip-slip throw. We can speculate that the total amount of deformation is likely to be lower (second order) for an en echelon basin, being induced by a partial transfer of motion from the master strike-slip fault zone.

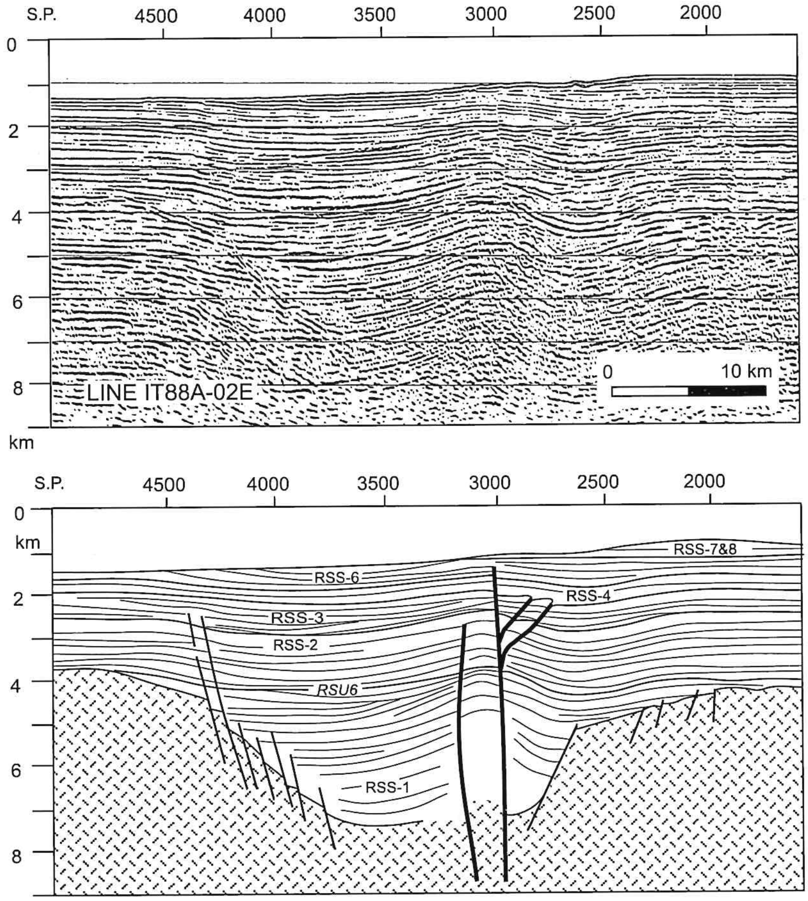

Fig. 5 - Example of an inverted along strike basin in the depth-converted seismic line IT02E.

The most evident example of an en echelon inverted basin in the Ross Sea is the Terror Rift (Fig. 1), a deep tectonic trough that developed during the last 30 Ma within the pre-RSU-6 Victoria Land Basin. The kinematic origin of the Terror Rift as an extensional-transfer basin at the southern tips of the Priestley and Campbell right-lateral strike-slip fault zones has been proposed by Salvini et al. (1997b). According to this interpretation the Terror Rift has developed as a transtensional basin that accommodates part of the horizontal displacement along the strike-slip fault zones onshore. Right lateral strike-slip motion was transferred to the basin-controlling faults, especially in the eastern shoulder. This produced local inversion and positive flower structures generated (Fig. 6).

ACROSS STRIKE BASINS

Pre RSU-6 basins that are oriented at a high counterclockwise angle with respect to the post RSU-6 regional right-lateral strike-slip fault zones (*i.e.* ENE-WSW to NE-SW) are named across strike basins (Fig. 3). Such weaker crustal zones in the thinned continental crust of the Ross Sea did not generally influence the forward propagation of the post-RSU-6 strike-slip belts and no or a very few strike-slip motion is likely to be transferred to the basin-controlling pre RSU-6 faults. Across strike basins trend at a high angle to the maximum compressional axis in the borderland zones between the strike-slip regional faults (Figs. 3 & 7). This implies that pre-existing faults may undergo positive inversion with a major component of dip-slip thrusting. Moreover, all the pre RSU-6 extensional faults in the basins undergo the same compressional stress and, consequently, may potentially re-activate. Across strike basins may undergo total inversion, according to the conceptual cross section in figure 7b.

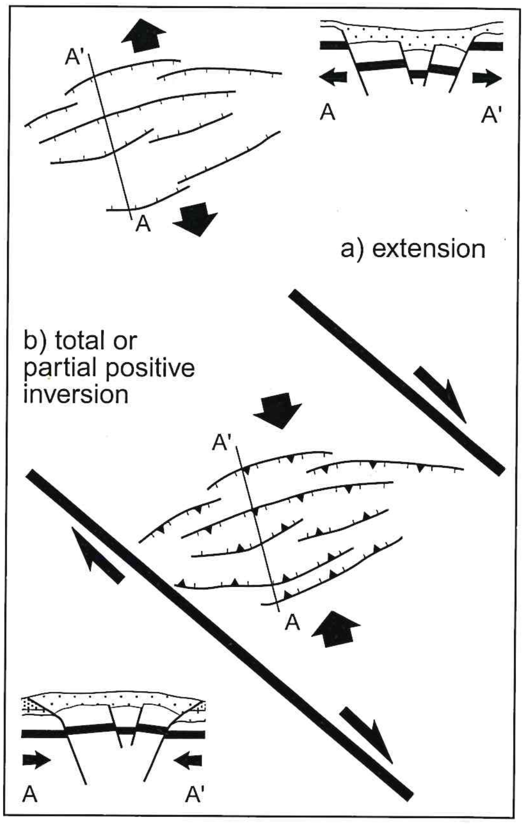

Fig. 7 - Conceptual map view and cross section of an across strike basin. *a)* Pre-inversion extensional basin; *b)* inversion of the basin-controlling faults.

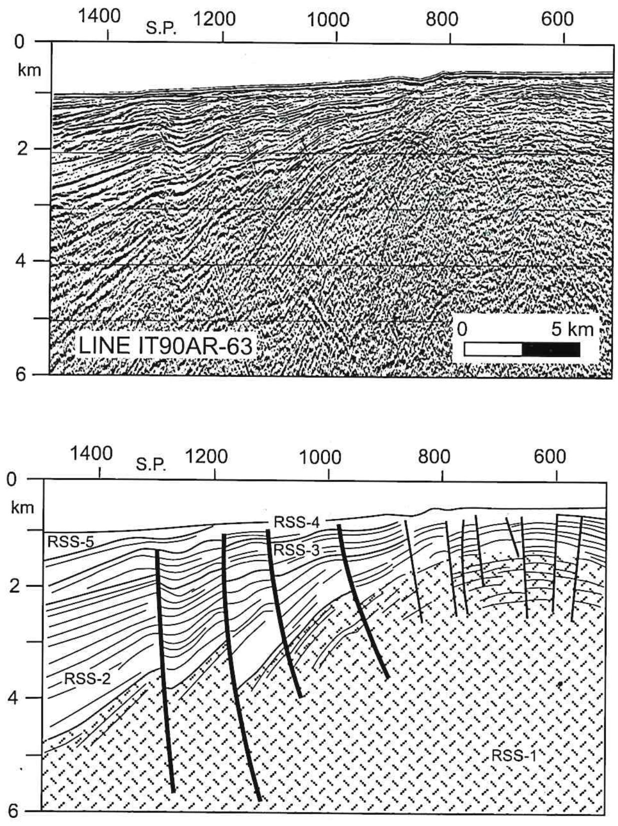

Fig. 6 - Example of an inverted en echelon basin in the depth-converted seismic line IT90AR-63.

An example of an inverted pre RSU-6 across strike basin in the southern Central Trough is shown in figure 8. Anticlinal folding is well evident in the southeastern shoulder of the basin. No post RSU-6 major faults and/or positive flower structures can be imaged in the seismic profile. Instead, the occurrence of a decollement can be assumed in the basal part of the seismic succession thus favoring dip-slip thrusting.

KINEMATIC VERSUS DYNAMIC INVERSION

Along strike basins undergo re-activation when some of the pre-existing basin-controlling faults become involved into the regional strike-slip fault zones during their forward migration. Pre-existing extensional faults may re-activate with a major horizontal component induced by the parallel or near parallel younger strike-slip faults. Displacement is transferred from the strike-slip faults to the pre-existing extensional ones, and in turn to the newly forming strike-slip faults at the outward tip of the inverted basin. This means that positive inversion is generated by the relative motion along the master strike-slip faults. Basin re-activation is local, largely transpressional and is referred to as a kinematic inversion *sensu* Davis (1984).

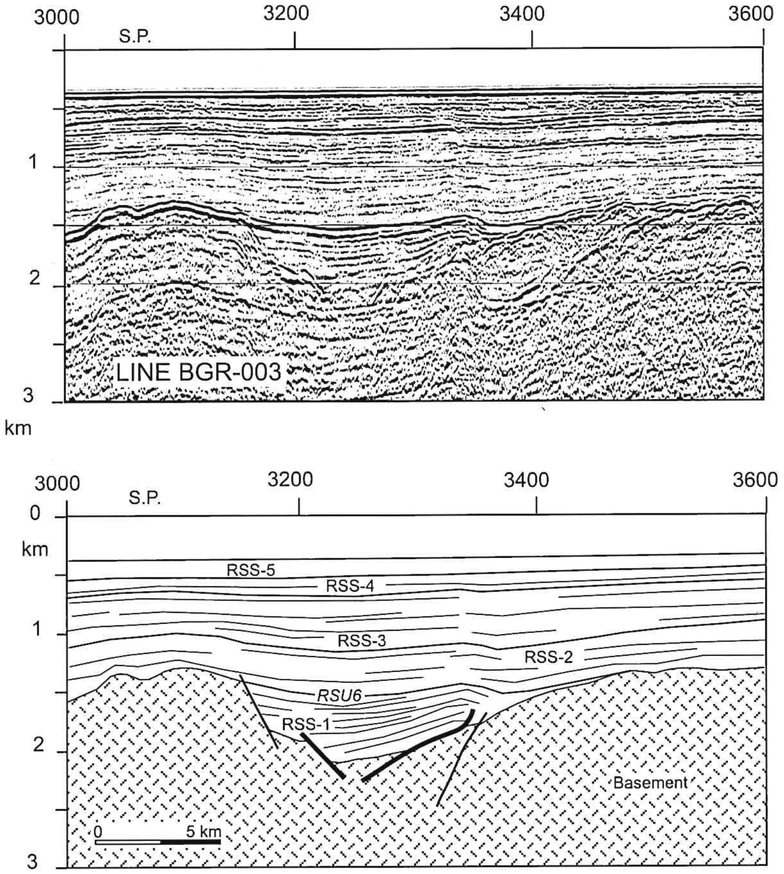

Fig. 8 - Example of an inverted across strike basin in the depth converted seismic line BGR003.

The inversion mechanisms of en echelon basins are similar to those acting during the compressional re-activation of along strike basins. A partial transfer of the strike-slip displacement to the basin-controlling pre-RSU6 faults may occur in the transtensional framework. Basin inversion is local, largely transpressional, and kinematically linked to the strike-slip displacement along the re-activated basin-controlling faults. As in the along strike basins, positive re-activation of en echelon basins is generated by the relative motion along strike-slip or transtensional faults and is again referred to as kinematic inversion *sensu* Davis (1984).

Positive inversion of across strike basins is induced by the compressional stress in the borderland zones of the right-lateral strike-slip faults. Transfer of strike-slip motion between the strike-slip fault zones and the pre RSU-6 extensional faults is very limited. Fault re-activation develops mainly as reverse faulting and thrusting, with subordered transpression. This means that inversion of across strike basins does not relate to the relative motion along the strike-slip master faults, but to the dynamic interfault stress in the borderland zones. For this motive, inversion of across strike basins is referred to as a dynamic inversion.

CONCLUSIONS

Three dimensional analysis of the reflection seismic dataset of the Ross Sea has allowed identification of the occurrence of post RSU-6 positive inversion affecting some pre RSU-6 extensional basins. Basin inversion developed within the right-lateral strike-slip tectonic framework that has been controlling the evolution of the Ross Sea Region for the last 30 Ma.

Based on the relative orientation between the regional strike-slip fault zones and the pre RSU-6 inverted basins, three geometric patterns have been defined in the Ross Sea: along strike basins, en echelon basins and across strike basins. Basin inversion within along strike and en echelon basins relates to a kinematic inversion induced by the relative motion of tectonic blocks. Across strike basins lie in the borderland zones of the right lateral strike-slip master faults and underwent a dynamic inversion, related to the interfault dynamic stress field. The different styles of inverted basins identified in the Ross Sea provides new details that well fit into the regional strike-slip and extensional Cenozoic evolution of the Ross Sea Region.

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