Polygonal Fault System in the Cretaceous of the Magallanes Basin, Southern Chile*

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Search and Discovery Article #10641 (2014)
Posted September 22, 2014

*Adapted from extended abstract prepared in conjunction with oral presentation given at AAPG International Conference & Exhibition, Istanbul, Turkey, September 14-17, 2014, AAPG © 2014

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Abstract

High resolution 3-D seismic data and the use of seismic attributes reveal a fault-deformed interval in the Upper (Cenomanian-Maastrichtian) Cretaceous, fine-grained marine deposits of the Magallanes Basin, southern Chile. This singular interval is bounded below and above by a relatively undisturbed stratigraphy characterized by continuous reflections; the bounding surfaces coincide with regional unconformities. The layer-bound nature and widespread distribution of the faulted interval, together with the near-isotropic distributions of fault strikes and the polygonal configuration in plain view, suggest that it represents a diagenetic rather a tectonic feature compatible with a polygonal fault system (PFS). There are two stratigraphic layers ("tiers") in the deformed interval separated by an important unconformity. Although deformation style is similar in both tiers, the lower tier is simple and shows larger and more regular-shaped (rectangular to pentagonal) polygons in comparison to the more complex upper tier, which is characterized by smaller and rather partial polygons to spindle-shaped faults. Fault lengths in the lower tier range from 100-2000 m, whereas in the upper tier they range from 40-650 m; in both tiers fault throws average ~40-50 m. Because PFSs may potentially control basin-wide fluid flow and compartmentalization distribution, a better understanding of the Cretaceous PFS may be a key not only for future well and reservoir management but also for the implementation of new technologies, such as hydraulic fracturing and micro-seismic monitoring, in petroleum exploration and production in the region.

Introduction

Polygonal fault systems (PFSs) due to non-tectonic processes are one type of basin-wide diagenetic feature (Cartwright, 2011) common in deep-water, fine-grained sediments of many basins worldwide (Cartwright and Dewhurst, 1998; Cartwright, 2011). In contrast with tectonic fault systems, PFSs are thought to represent the combined action of volume compaction and water expulsion of swelling clays, horizontal stress decrease and episodic hydraulic fracturing (Cartwright, 1994; Cartwright and Lonergan, 1996). The most distinctive features of PFSs are the strata-bound nature of the system, the near-isotropic distributions of fault strikes and the meso-scale polygonal pattern in map view (Lonergan et al., 1998).

This preliminary report is part of a larger and ongoing project of the ENAP-Magallanes exploration team on the origin and distribution of PFSs in the Magallanes Basin, southern Chile, in order to assess and better understand their potential implications for future petroleum exploration and production strategies in the Basin. Within this broader framework and based on the interpretation of high-resolution 3D seismic and well data in the context of local stratigraphy, the purposes of this contribution are (1) to describe the widespread and well-developed PFS, and (2) to highlight its potential effects on the petroleum system of the study area.

Although polygonal fault patterns occur in Cretaceous to Paleogene strata and extent for approximately 12,000 km^2 in the Chilean portion of the Magallanes Basin, the primary study section is the Cretaceous in the Arenal and Intracampos blocks, located in the northern part of the Island of Tierra del Fuego, southern part of the Basin (Figure 1). The polygonal faults probably extent further to the north into the Argentine portion of the Basin (called Austral Basin). Belotti et al. (2013) described a complex fault system in the Lower Cretaceous Palermo Aike Formation compatible with a PFS. This older PFS suggests that conditions for the development of PFSs were already given in the Basin since the Early Cretaceous. The origin of this PFS is considered in the light of the aforementioned available hypotheses.

Geological Setting and Study Area

The interpreted 3D seismic surveys belong to the Arenal and Intracampos blocks located in the northern part of the Island of Tierra del Fuego, southern part of the Magallanes Basin (Figure 1). These blocks delimit conventional oil and gas fields in Jurassic to Lower Cretaceous reservoirs as well as important unconventional gas accumulations in Paleogene strata.

The Magallanes Basin, located in the southernmost part of South America, is bounded in the west and south by the Patagonian Andes fold-thrust belt and in the east by the Río Chico-Dungeness Arch. Towards the southeast, it connects with the Malvinas Basin and continues to the north into the Argentine territory where it is called the Austral Basin (e.g. Wilson, 1991; Ghiglione et al., 2010). The Magallanes Basin (Biddle et al., 1986), including both the Austral (Argentina) and Magallanes (Chile) portions, forms a NNW-trending depocenter that covers ~200,000 km^2 where a thick (>7 km) pile of sediments accumulated upon a Paleozoic metamorphic basement (Thomas, 1949; Biddle et al., 1986). Figure 2 shows a generalized stratigraphic section and main tectonic phases for the southern Magallanes Basin.

The geologic evolution of the Magallanes Basin has been mainly controlled by the interaction of the South America and Antarctic plates (e.g. Biddle et al., 1986). The development of the Magallanes Basin was initiated as an extensional basin during the break-up of Gondwana in the Late Jurassic, with active subsidence continuing throughout most of the Cretaceous until it was inverted into a foreland basin during the Late Cretaceous-Early Paleogene times (Wilson, 1991; Fildani et al., 2008; Ghiglione et al., 2010). Cenozoic subsidence was related to this last event and the formation of the fold-thrust belt on the west and south (Biddle et al., 1986).

In the study area, the Cretaceous stratigraphy is dominated by marine fine-grained terrigenous sediments and is characterized by a number of significant surfaces, most of which have been interpreted as unconformities. The basal TST unconformity separates the Late Jurassic volcaniclastic deposits of the Tobífera Formation from the main reservoir in the area, the Lower Cretaceous sandstones of the Springhill Formation (e.g. Biddle et al., 1986). The Upper Cretaceous Lutitas Gris Verdosas shales rest unconformably above the Margas marls along the unconformity C1. In the Upper Cretaceous two major erosional or non-depositional events are identified, one in the mid-Upper Cretaceous (I10) and a second in the Maastrichtian (Ks2). The top of the Cretaceous is marked by a regional unconformity (G7). This study focuses on the Upper Cretaceous, shale-dominated succession between C1 and Ks2 that is deformed by polygonal faults (Figure 3, Figure 4, Figure 5).

Implications and Future Work

The Magallanes Basin contains a number of small and medium sized oil and gas fields, and even though the Basin is in a mature stage it is still attractive for further exploration. To increase the understanding of both conventional and unconventional petroleum resources in the Magallanes Basin, it will be necessary to continue at least with the basic investigations. The recognition of polygonal faults in the Magallanes Basin would open up not only new migration and play models but also new strategies for future exploration and production management. It is widely recognized that faults may represent seals or permeable conduits for fluid flow in the subsurface (e.g. Caine et al., 1996; Hesthammer and Fossen, 2000). Even small scale faulting beyond seismic resolution may act as important flow barriers (e.g. Veeken, 2009). Bearing this in mind, a database relative to tier thicknesses, fault densities and fault lengths and throws would derive in the appropriate scale relations among fault attributes of different hierarchies, including the tectonic counterparts. Such supplementary information can be useful during well planning and future reservoir assessments.

Owing to the mature stage of the Basin and the continuous growth in energy demand, ENAP is starting to explore the shale oil/gas potential of the Lower Cretaceous Margas-Estratos con *Favrella* succession, the latter stratigraphic unit representing the major Cretaceous source rock in the Basin (Figure 2 and Figure 6). The petroleum recovery from these shaly units would be only improved with the use of new technologies such as hydraulic fracturing. However, given the fact that the fault-deformed interval is immediately above this potential unconventional play, the polygonal faults may pose a risk to the sealing capacity and consequently of potential leakage. In addition, polygonal faults may compartmentalize certain types of reservoir (e.g. Moller et al., 2004) and thus their recognition may be crucial to evaluate the discrete permeability structure and variable hydromechanical behavior of individual compartments. An understanding of the PFS in the area will also serve as the base for more appropriate conceptual and numerical models for flow simulation within the fault zones.

Lonergan and Cartwright (1999) in a case study from the Eocene Alba Field in the central North Sea demonstrated that polygonal faulting and large-scale modification of reservoir geometry through sand remobilization and withdrawal can be related processes that occur during early burial in the basin. In the study area, amplitude anomalies near some of the polygonal faults and the occurrence in outcrops of sand injectites in age-equivalent strata suggest that the PFS may have locally facilitated post-depositional remobilization and clastic injection. Gas chimneys or vents have also been associated with PFSs (e.g. Gay et al., 2006). Seismically disturbed zones interpreted as gas chimneys are common in the study area but there is no apparent link between them and the Cretaceous PFS in the Basin. These two aspects will be further investigated in the near future.

Conclusions

The polygonal fault system in the Upper Cretaceous of the Magallanes Basin extends over thousands of square kilometers, implying an event of regional scale in the Basin. In the study areas, the strata-bounded nature of the fault-deformed interval and its characteristic polygonal pattern in plan view suggest that the system is a diagenetic rather a tectonic feature. The interval was divided into two stratigraphic layers (tiers), a simple and mature lower tier and a more complex and less mature upper tier. In both tiers, faults have no preferred directions. No link could be established between tier thickness and fault size or throw.

Because PSFs are laterally extensive features and their formation is dependent, among other factors, on grain-size and lithology, they can be used as a correlation tool for basin-wide stratigraphic correlations.

From a petroleum system perspective, the Cretaceous PSF in the Magallanes Basin constitutes a potentially fundamental control on reservoir geometry, production characteristics and fluid flow on a regional scale. On account of the occurrence and significant lateral extent in the Magallanes Basin, it will be necessary to do further investigation on the genesis and actual distribution of the PFS in order to better understand the possible effects of this singular fault-deformed interval on more local fluid dynamics and reservoir compartmentalization. An understanding of the distribution of the PFS in the Magallanes Basin may also provide important clues for future reservoir management, well planning and implementation of new technologies (such hydraulic fracturing and microseismic monitoring) in petroleum exploration and production in the region.

Acknowledgments

The authors thank the management of ENAP-Magallanes for granting the permission to publish this manuscript.

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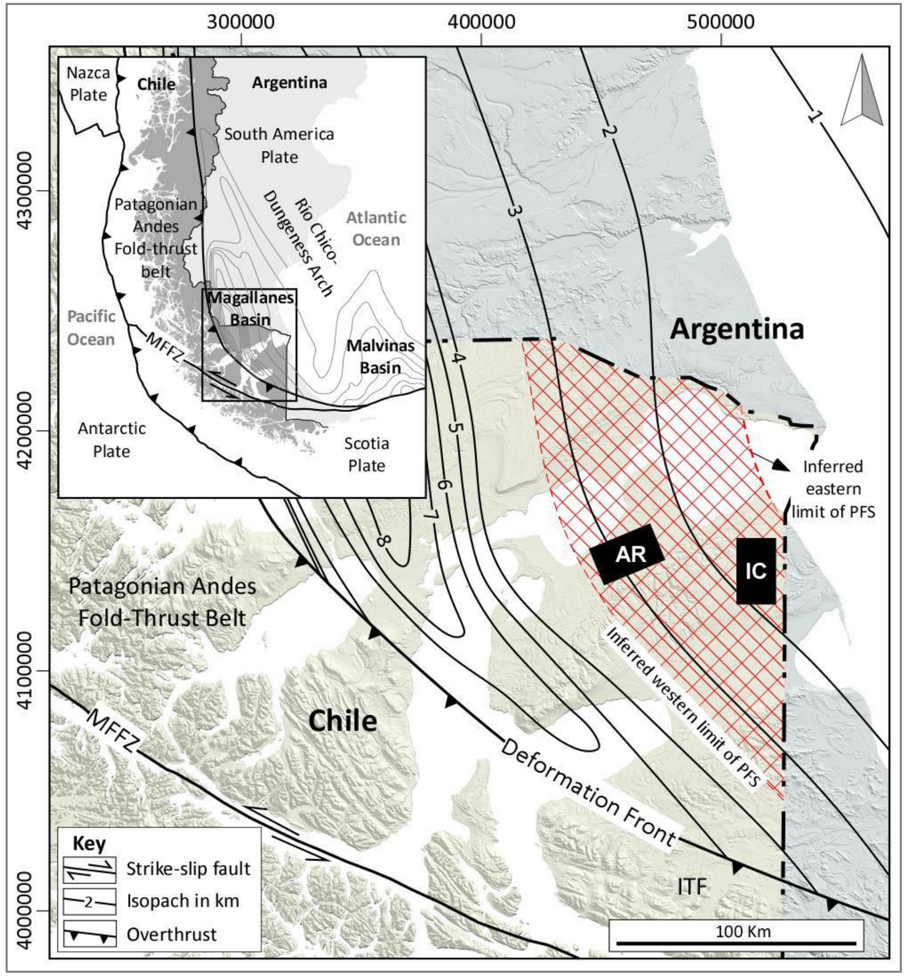

Figure 1. Location map showing the study area seismic surveys (black boxes, AR = Arenal block and IC = Intracampos block) in the southern Magallanes Basin. Inset shows location of the Magallanes Basin. Red cross-hatched pattern indicate inferred lateral extent of the Cretaceous polygonal fault system in the Chilean portion of the Basin. ITF = Island of Tierra del Fuego; MFFZ = Magallanes-Fagnano Fault zone.

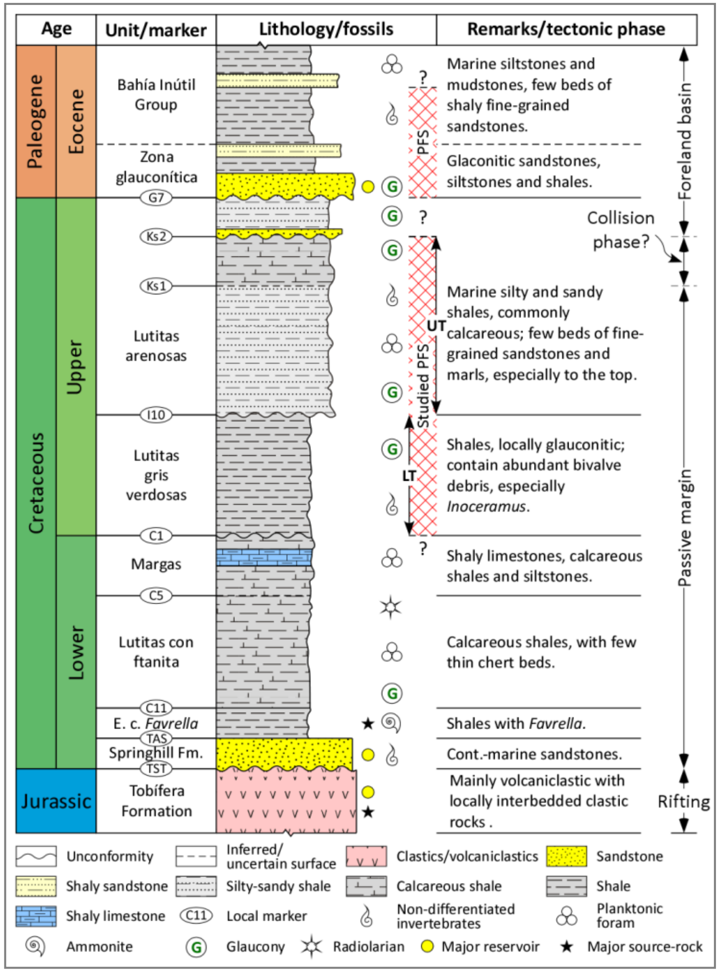

Figure 2. Generalized columnar section of the Chilean portion of the Magallanes Basin showing stratigraphic nomenclature, typical fossil and mineral content, main tectonic phases and the two polygonal fault systems (PFS, red crosshatched zones) recognized in the Basin. The studied Cretaceous PFS is divided into two stratigraphically bounded layers or "tiers" (lower, LT, and upper, UT). E. c. *Favrella* = Estratos con *Favrella*.

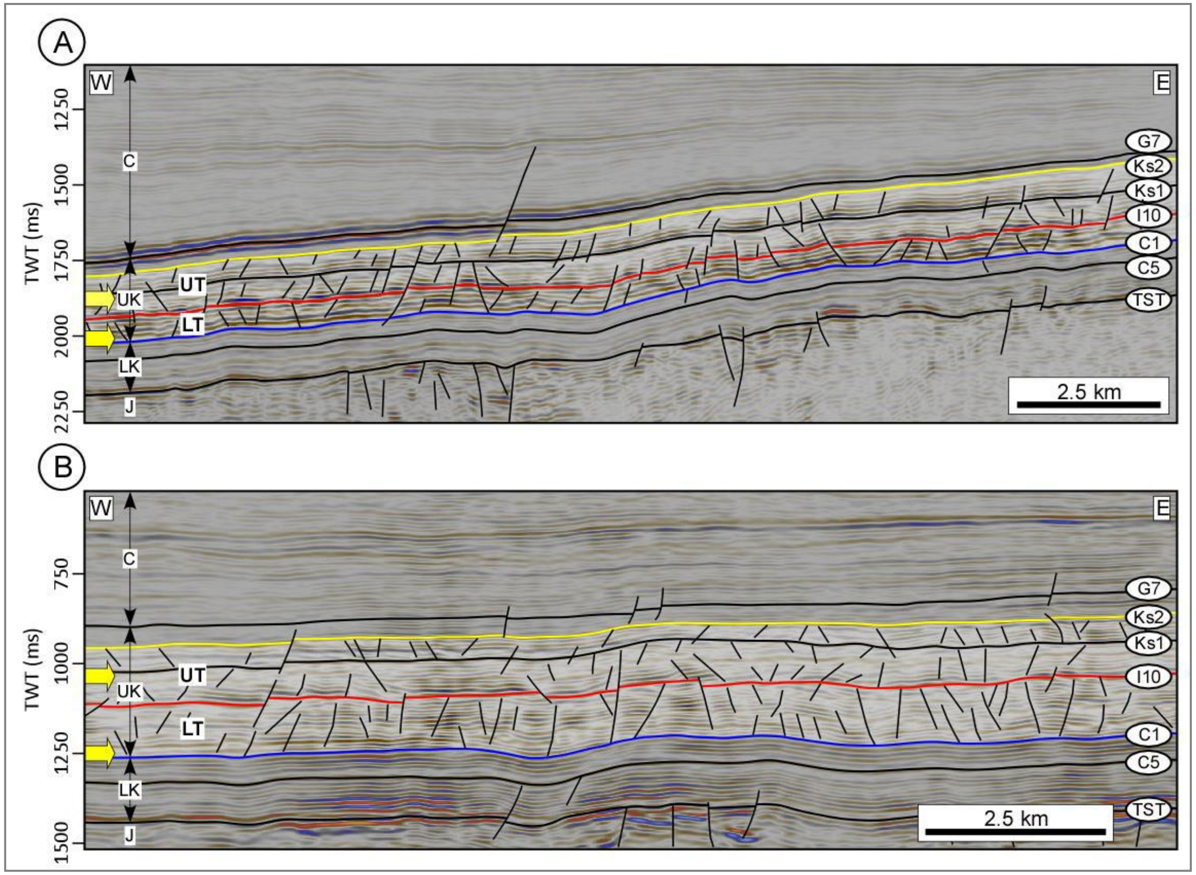

Figure 3. Representative seismic time profiles illustrating the seismic expression, geometry and distribution of polygonal faults in the Upper Cretaceous of the Arenal (A) and Intracampos (B) blocks. Vertical exaggeration is about 5x for (A) and about 5.5x for (B). In both areas, the seismic horizon I10 (in red), interpreted as a mid-Upper Cretaceous unconformity, separates an essentially simple lower tier (LT) that started to developed in the lowermost Upper Cretaceous (interpreted unconformity C1, in blue) from a more complex upper tier (UT) that ends along the seismic horizon Ks2 (in yellow), interpreted as a Maastrichtian unconformity. Yellow arrows on the left of the panels indicate slicing level on Figure 4. J = Jurassic, LK = Lower Cretaceous, UK = Upper Cretaceous, C = Cenozoic.

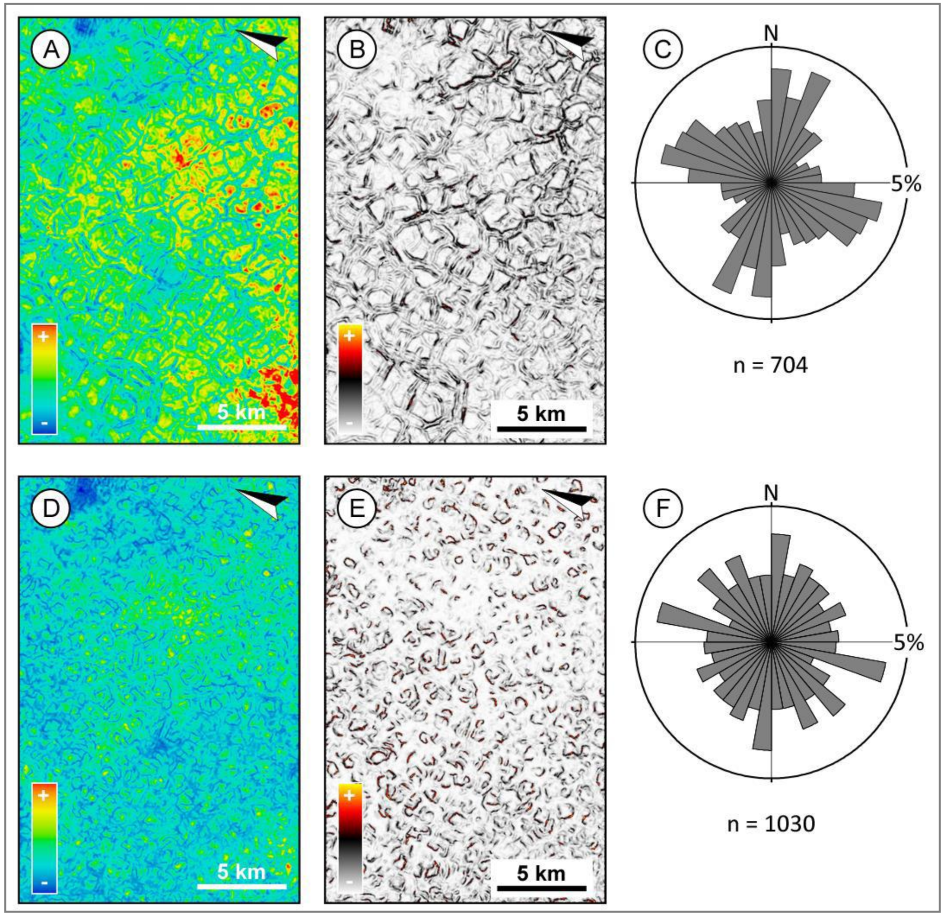

Figure 4. Seismic attribute maps and equal-area rose diagrams of polygonal fault-segment orientations for the lower (A-C) and upper (D-F) tiers in the Arenal block; slicing level indicated in Figure 3A. (A) RMS amplitude taken from 50 ms thick extraction window above the seismic horizon C1 (base of the PFS); (B) variance slice along the seismic horizon C1; (C) equal-area rose diagram of fault-segment orientations for the fault map of (B). (D) RMS amplitude taken from 50 ms thick extraction window above the seismic horizon I10; (E) variance slice along the seismic horizon Ks1; (F) equal-area rose diagram of fault-segment orientations for the fault map of (E).

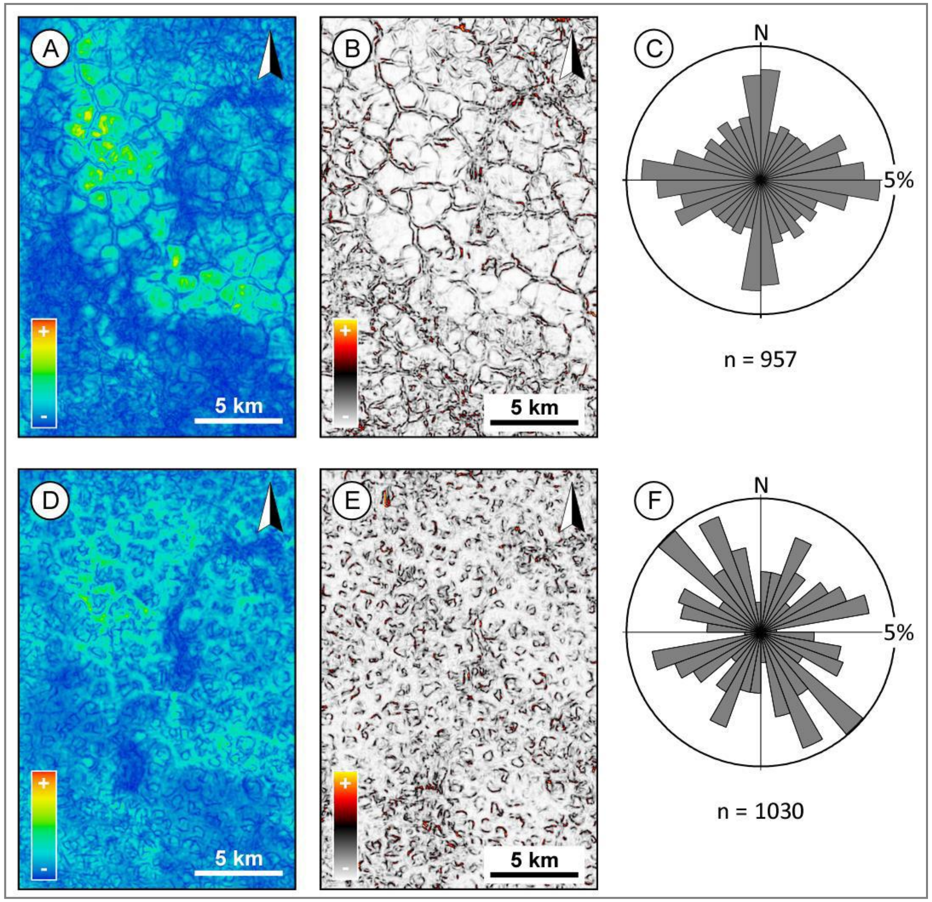

Figure 5. Seismic attribute maps and equal-area rose diagrams of polygonal fault-segment orientations for the lower (A-C) and upper (D-F) tiers in the Intracampos block; slicing level indicated in Figure 3A. (A) RMS amplitude taken from 50 ms thick extraction window above the seismic horizon C1 (base of the PFS); (B) variance slice along the seismic horizon C1; (C) equal-area rose diagram of fault-segment orientations for the fault map of (B). (D) RMS amplitude taken from 50 ms thick extraction window above the seismic horizon I10; (E) variance slice along the seismic horizon Ks1; (F) equal-area rose diagram of fault-segment orientations for the fault map of (E).

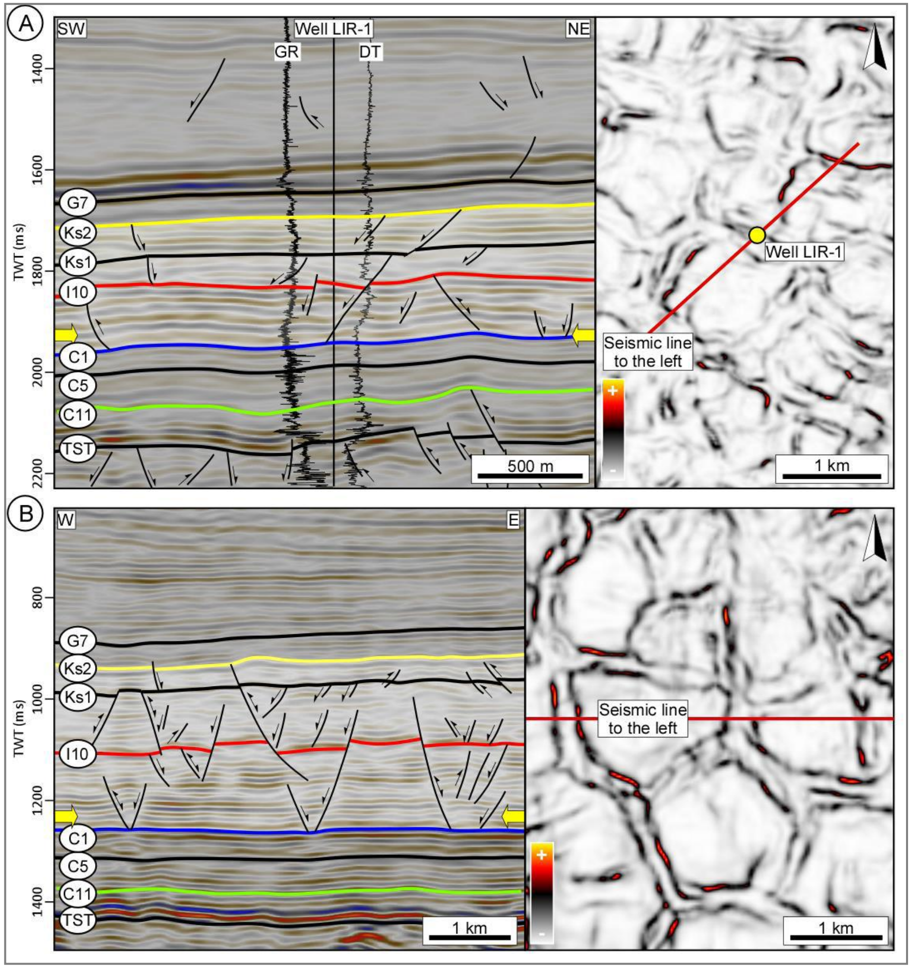

Figure 6. Seismic time profiles and variance slices showing a closer view of the seismic expression and geometry of polygonal faults in the Arenal (A) and Intracampos (B) blocks. Yellow arrows on the seismic sections indicate the approximate level at which the variance slices were extracted. GR = gamma-ray, DT = sonic; TST = top Jurassic seismic horizon; C11 = top of main source rock in the Basin; C1 = top Lower Cretaceous seismic horizon; G7 = top Cretaceous seismic horizon.