Structural and stratigraphic aspects of salt tectonics in the Eastern Brazilian margin: evolution model and seismic section restoration

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Abstract

Complex geological features, observed in seismic sections along the Eastern Brazilian margin sedimentary basins, were structurally reconstructed by a restoration technique. The area is located between latitudes 20^0S and 27^0S and longitudes 38^0W and 48^0W, encompassing Santos and Campos basins.

Salt tectonics structural styles along the South Atlantic divergent margins may be divided into five tectonic compartments, extending from the proximal region, along the rift border, towards the oceanic crustal limit, in the deep water region. The interpretation of the seismic sections describes structures belonging to all those compartments. Therefore, analyzing extensional and compressional domains along the seismic profiles constitutes an important advance to understand the petroleum geology of those basins.

The balancing of structural sections can easily be conducted using computer programs based upon the line length and area conservation law. The restoration method was a combination of the algorithms *Vertical/Oblique Slip* and *Flexural Slip*. The restoration itself does not necessarily indicate that the original seismic interpretation is correct and unique. But it may provide clues that indicate which alternative interpretations are viable and which are more plausible. The techniques applied during the construction of the structural sections indicate which layers presented rock excess and which had mass deficit, so the original structural interpretation can be adjusted according to the observed discrepancies.

The seismic sections restoration indicates different ratios of extension for each stratigraphic age. The ratio of extension for the turtleback (*Casco de Tartaruga*) section was about 9,7%. The ratio of total extension was calculated from the ratio between the deformed length of each stratigraphic layer and the original, pre-extension length. It is suggested that the climax of extensional episodes coincides with major tectonic events along the continental margin.

Introduction

Salt tectonics is associated with the formation of multiple stratigraphic and structural plays in Campos and Santos basins. Consequently it is responsible for a large proportion of the hydrocarbon accumulations in those basins. The main plays associated with salt tectonics are structural, particularly roll-overs and turtlebacks. Stratigraphic traps are associated with listric growth faults controlling sandstone turbidites and also porous facies distribution in carbonate rocks (Figueiredo and Mohriak, 1984; Mohriak et.al., 1995).

Method

The adopted methodology was based upon digitizing interpreted seismic sections and restoration of the stratigraphic sequences through the Vertical / Oblique Slip algorithm, available in the software GeoSec2D® (Paradigm).

The faults generated by the halokinetic movements are followed by the collapse of blocks. This is due to the lack of stability when they are separated by extensional tectonics. This downfaulting is oriented according to a direction relative to the main stress vector (angle). Generally this direction is close to the vertical axis, coinciding with the gravity force. The blocks collapse by shear displacements along the fault planes. Thus the layers are plastically deformed as they rotate along the faults. Parts of the collapsed block move along the fault plane with differential displacement according to the fault throw. The shear displacement is a vector that can be applied to a component of the block, i.e., a group of geometric elements within the blocks. A field of displacements (or deformations) is applied to this component. Such field configures a group of parallel lines.

Each line is associated to a single displacement that varies according to the measured distance from the top surface, down to the fault plane (Figure 1). Two approaches for the restoration are possible in this case: *fault template* and *horizon template*. The first arbitrates the fault plane as the reference surface, i.e., the measurement starting point. The second takes the top horizon. Similar mechanism is used when rebuilding the original geometry, in the *retro-deformation* process for a single component. Each vertice of the component is submitted to the specific field of displacement.

Stratigraphy

The regional profile in the Campos Basin (Figure 2 and Figure 3) shows three major megasequences: the syn-rift (Neocomian-Barremian), the transitional or evaporitic (Aptian) and the post-rift (Albian – Recent). In terms of salt tectonics, the post-tectonic sequence is separated from the syn-tectonic by a regional unconformity in the Late Tertiary. In the syn-tectonic sequence the units corresponding to Mid-Late Cretaceous and Early-Mid Tertiary thickens noticeably, as a consequence of stratigraphic expansion of the sedimentary layers during activity of the listric faulting (Figure 3).

Structure

The *turtleback* section (Figure 3) belongs to proximal and intermediate extensional tectonic domains of the Campos Basin (Fernandez, 2003). The following structural features are interpreted in the profile: listric normal faults, salt rollers, fault welds, turtlebacks, salt pillows and salt diapirs.

Four major fault systems can be observed: (1) synthetic normal faults associated with platform collapse, active from Albian up to Campanian; (2) listric normal faults, detaching at the salt base, which were active or reactivated from Albian up to Upper Miocene; (3) antithetic normal faults, associated with the extensional compensation of the synthetic faults; and (4) basement-involved normal faults, both synthetic and antithetic.

The structure imaged on the turtleback section may be modelled by physical experiments using silicone and sand layers to simulate the evaporite sequence and the overburden, respectively. These models (example, Figure 4) indicate a mechanism of thin-skinned extension resulting in rise and fall of diapirs and formation of turtleback structures (Vendeville and Jackson, 1992).

Results

The turtleback section, originally interpreted by Mohriak et al. (1995), was re-interpreted in depth, so that no scaling to depth was necessary in the restoration process.

Figure 5 shows the geodynamic evolution of the structure by sequential diagrams representing instant snapshots at specific ages. The deeper sequence or presalt strata (Barremian-Neocomian age and basement) was restored as a separate unit, because it was not affected by the salt tectonics. In deep water areas, the volcanic basement was the only unit to be restored, and we note that the Barremian-Neocomian syn-rift sequence is eroded there. This pre-salt unit has the upper portion affected by a breakup unconformity, therefore the estimate of the original thickness is not feasible.

In the upper sequence, the units aged Miocene to Pleistocene are post-tectonic, having mild faulting with small throws and neglible growth, therefore they can be removed from the section, so that there is no need to restore up to the top of those units. For the other units of the syn-tectonic sequences, we used the Vertical/Oblique slip algorithm to restore to the predeformation stage.

Based upon seismic and well data, the thickness and length of the layers in the interpreted section were corrected and restored again to the top of those units, in order to minimize the small interpretation mistakes.

The Paleocene/Upper Cretaceous unit is syn-depositional in the southeastern portion of the section. The Campanian/Turonian and Cenomanian units show some thickening towards the southeast.

During restoration, different extension ratios for each depositional unit can be calculated. Figure 6 shows an example, where the X axis represents the absolute age in million years (estimated by paleontological dating), while the Y axis represents the total extension ratio (km) for each restored unit.

Conclusions

We observe a gradually increasing extension of the early post-salt strata along the profile. This was initiated during the Albian and extended in time to the Late Cretaceous – Early Tertiary, when a stronger extension occurs, reaching a total extension apex by the Middle Eocene. By comparing the extension ratio of the first three units (Albian, Cenomanian and Campanian / Turonian), to the total extension in the Tertiary, one can observe an increment of almost 100% at the Eocene unit.

From the Eocene up to the Oligocene the total extension ratio decreased and we obtained a net compression from the Oligocene to the Miocene, with length reduction around 1.5 km. The length of the profile was kept constant, with neglible extension, from Miocene to Pleistocene and Recent. The total extension ratio (the ratio between the layer length after extension and the original layer length) at the turtleback section in Campos Basin is estimated as 9.7%.

We suggest that the higher extension rate during the Eocene might be triggered by volcanic activity and massive clastic progradation from the uplifted source areas towards the deeper basin.

The application of the restoration methodology of balanced sections is highly recommended when making structural interpretation and hydrocarbon exploration in complex structures zones, particularly in areas affected by salt tectonics and compression. It's an important tool in defining the best interpretation among possible alternatives. By respecting the structural styles observed in a given area and honoring the available data, one can reach a better understanding of the structures and the probable sequence of deformation, extracting clear exploratory advantages.

Acknowledgments

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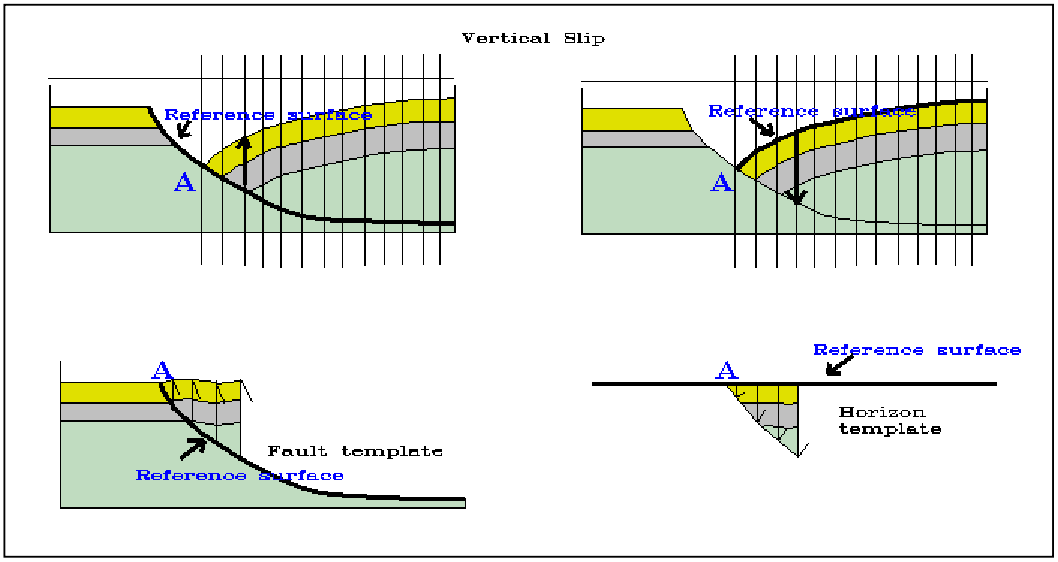

Figure 1 - Methodology of balancing a regional profile.

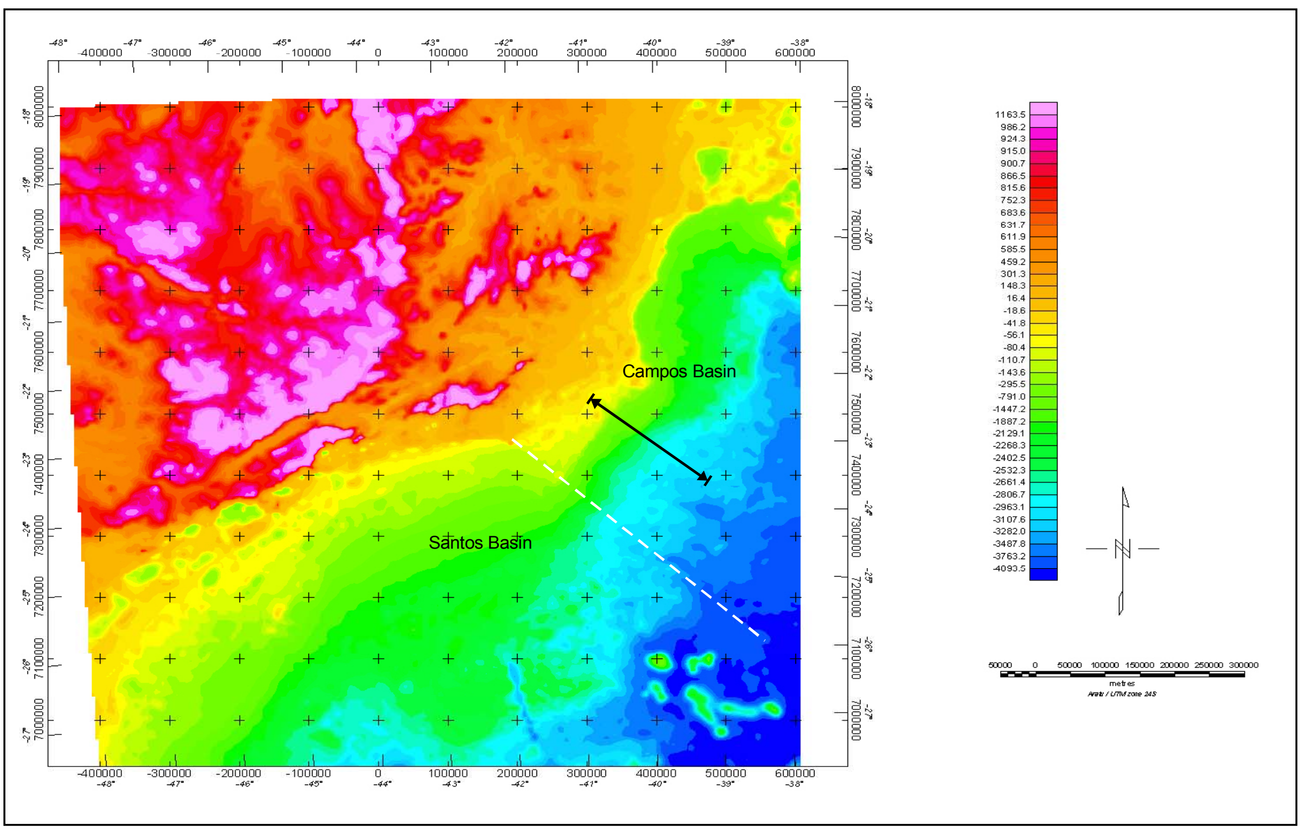

Figure 2 – Regional topographic and bathymetric map of the Eastern Brazilian margin. The black line shows the location of a regional seismic profile in the Campos Basin.

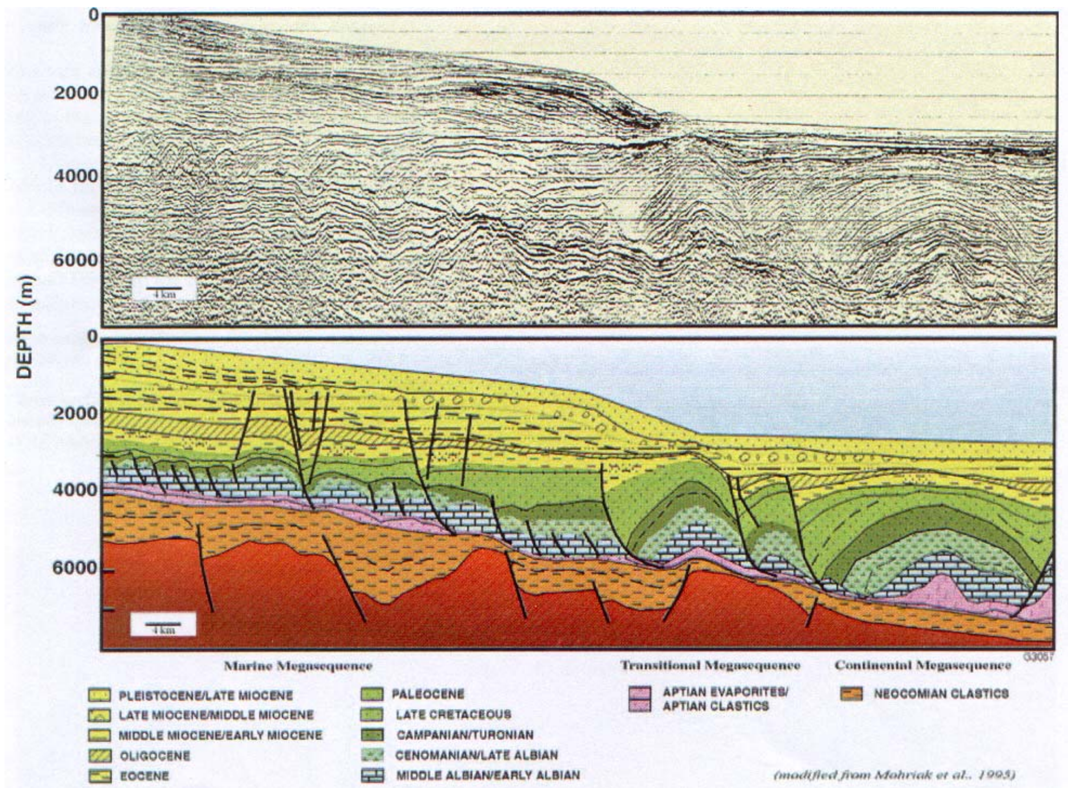

Figure 3 – Seismic profile (depth-converted) in the Campos Basin with schematic interpretation.

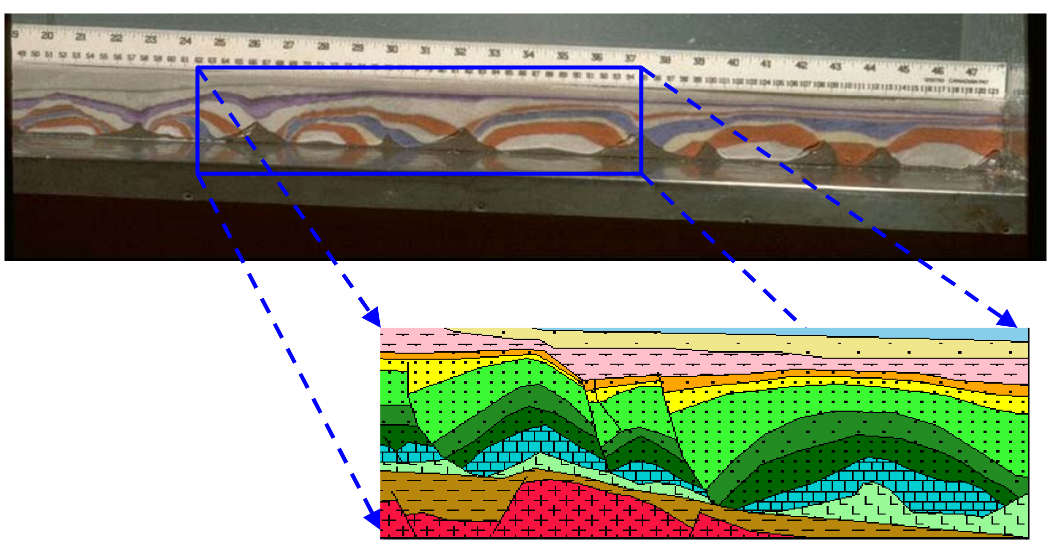

Figure 4 – Physical model experiment showing extensional tectonics and formation of turtlebacks Geological model shows a re-interpretation based on seismic restoration.

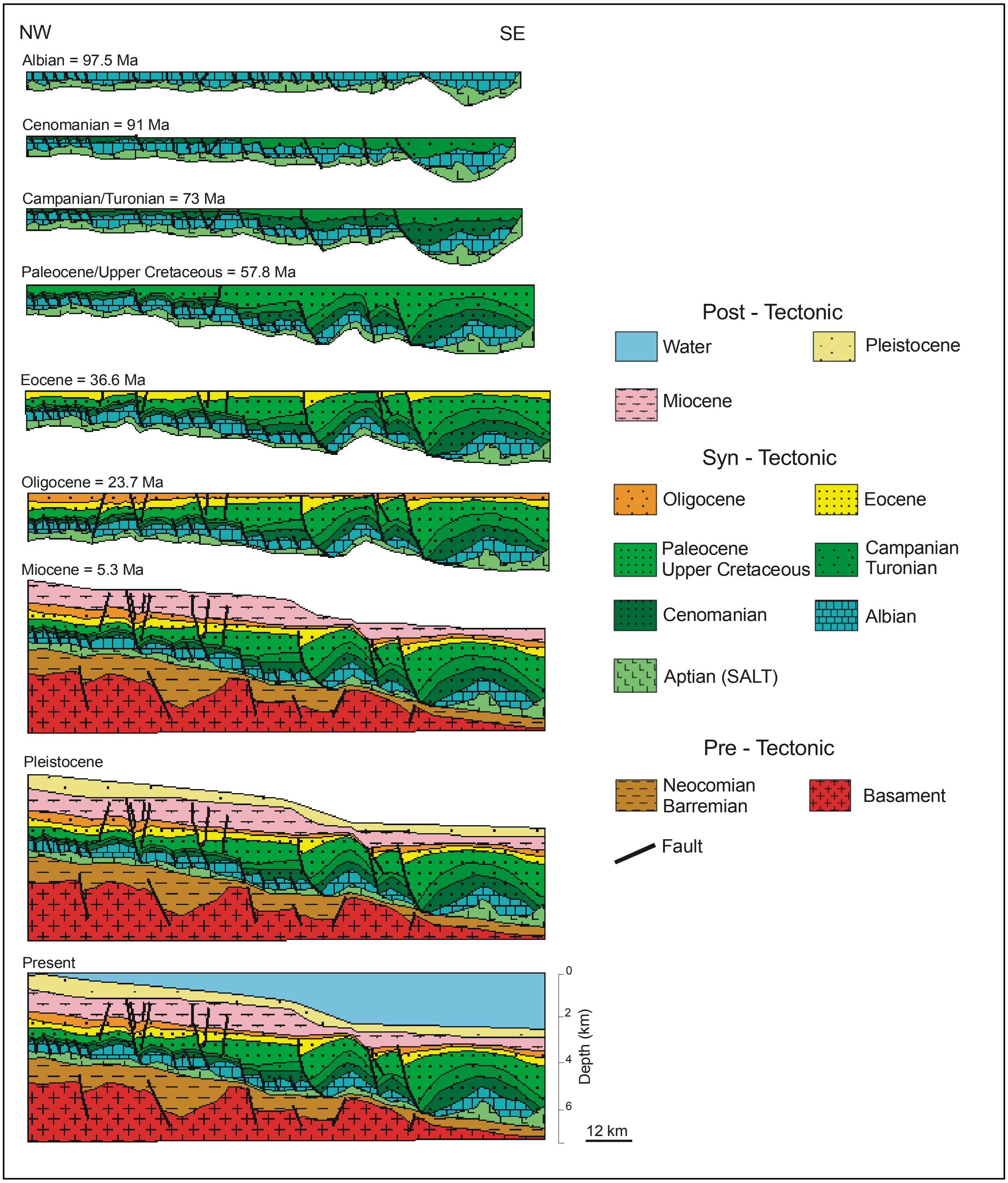

Figure 5 – Restoration of regional profile in the Campos Basin with evolution model for salt tectonics.

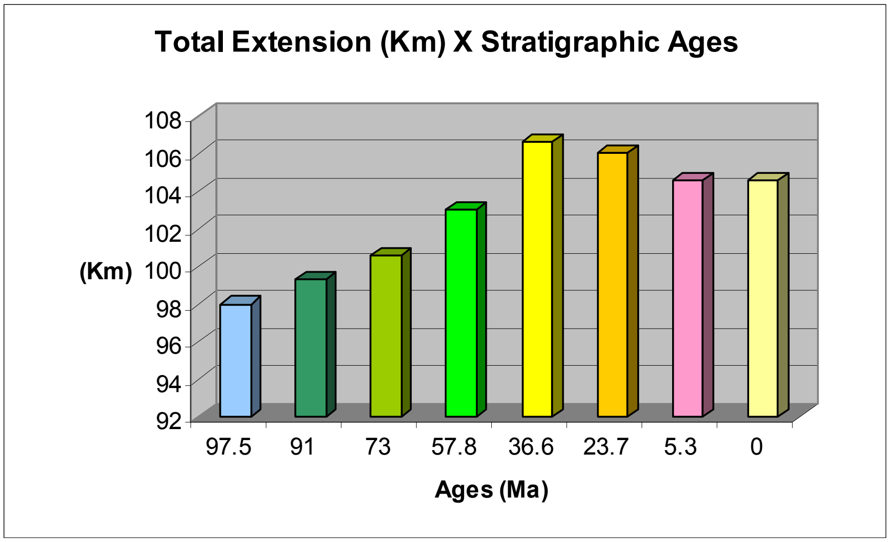

Figure 6 – Graph showing total extension vs. stratigraphic ages along the turtleback structure seismic profile.