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FORCED-FOLD STRUCTURES IN THE MANNAR BASIN, SRI LANKA: MODES OF OCCURRENCE, DEVELOPMENT MECHANISM AND CONTRIBUTION FOR THE PETROLEUM SYSTEM

E.K.C.W. KULARATHNA[1,*], H.M.T.G.A. PITAWALA[2], A. SENARATNE[2], B.S.M.C.K. SENEVIRATHNE[1], D.A.WEERASINGHE[1]

[1]*Petroleum Resources Development Secretariat, Colombo 01, Sri Lanka*

[2]*Department of Geology, Faculty of Science, University of Peradeniya, Sri Lanka*

[*]*Corresponding Author: e-mail: kularathna@prds.lk*

ABSTRACT

Mannar Basin, which lies from Southwest to Northwest offshore Sri Lanka and South of the Cauvery Basin is a pre-cratonic failed rift basin dominated with igneous activities. Forced-fold structures developed due to igneous activities are common in the Basin, and one of the gas discoveries in the basin, Dorado was encountered in such a structure. Based on the available data and seismic data (both 2D & 3D), the present study was carried out to understand the modes of occurrence of forced fold structures and their relationship to the petroleum system of the basin. Forced-folds occur more frequently towards the present day depocenter of the basin, as isolated structures or as clusters between the horizons of Cretaceous top and Albian-Aptian. Noticeable folding at the horizon of Cretaceous top suggests that the sill intrusions related folding had been developed during Maastrichtian (~66Ma) age. Areas with intense shallow level sills may have formed clusters of forced-folds at the location and they may have caused for the development of large scale dome like structures at the level of top Cretaceous horizon with significant vertical relief over a large area. The developed structures could offer regional scale dip and fault bounded closures for large volumes of hydrocarbon accumulations. An extrusive flood volcanic layer covering more than two thirds of the area in the Sri Lankan jurisdiction of the Mannar basin, that exists just above the Cretaceous top horizon could act as a regional seal above the top Cretaceous horizon. Main potential source rock intervals are present in the Mesozoic section have generated significant volumes of oil and gas after 55 Ma. Therefore, isolated and clusters of forced-fold plays may bear significant volumes of hydrocarbons if the rest of the required elements necessary for petroleum system elements are present.

***Key words:** Sri Lanka, Mannar Basin, petroleum system, Forced-fold structures, Flood volcanic*

INTRODUCTION

Basins dominated with igneous activities have traditionally been avoided by hydrocarbon exploration companies, mainly because of the challenges in imaging and the perceived detrimental effect of igneous activity on the petroleum system. However, the igneous activities in basins could demonstrate a positive effect on a petroleum system such as opening up of new play types (Rohrman, 2007). Mannar Basin, which lies from Southwest to Northwest coastal line of Sri Lanka, Southeast of India and South of the Cauvery Basin, is a pre-cratonic failed rift basin dominated with igneous activities (Figure 1). In terms of size, the Sri Lankan side of the Mannar Basin approaches an area of approximately 42,000 km^2 and shows certain geological structures, developed under the influence of igneous activities, such as forced fold structures or traps generated by sill jack-up (Pollard and Johnson, 1973; Hansen, 2004). These structures are clearly noticeable in the available seismic data (Figure 5) and are commonly found in the basin.

FORCED FOLD STRUCTURES / JACKED-UP STRUCTURES

Forced-folds or jacked-up structures associated with igneous intrusions have been studied since several decades ago (Du Toit, 1920; Loewinson-Lessing, 1936; Hotz, 1952). However, the limitations at outcrop level have hindered the

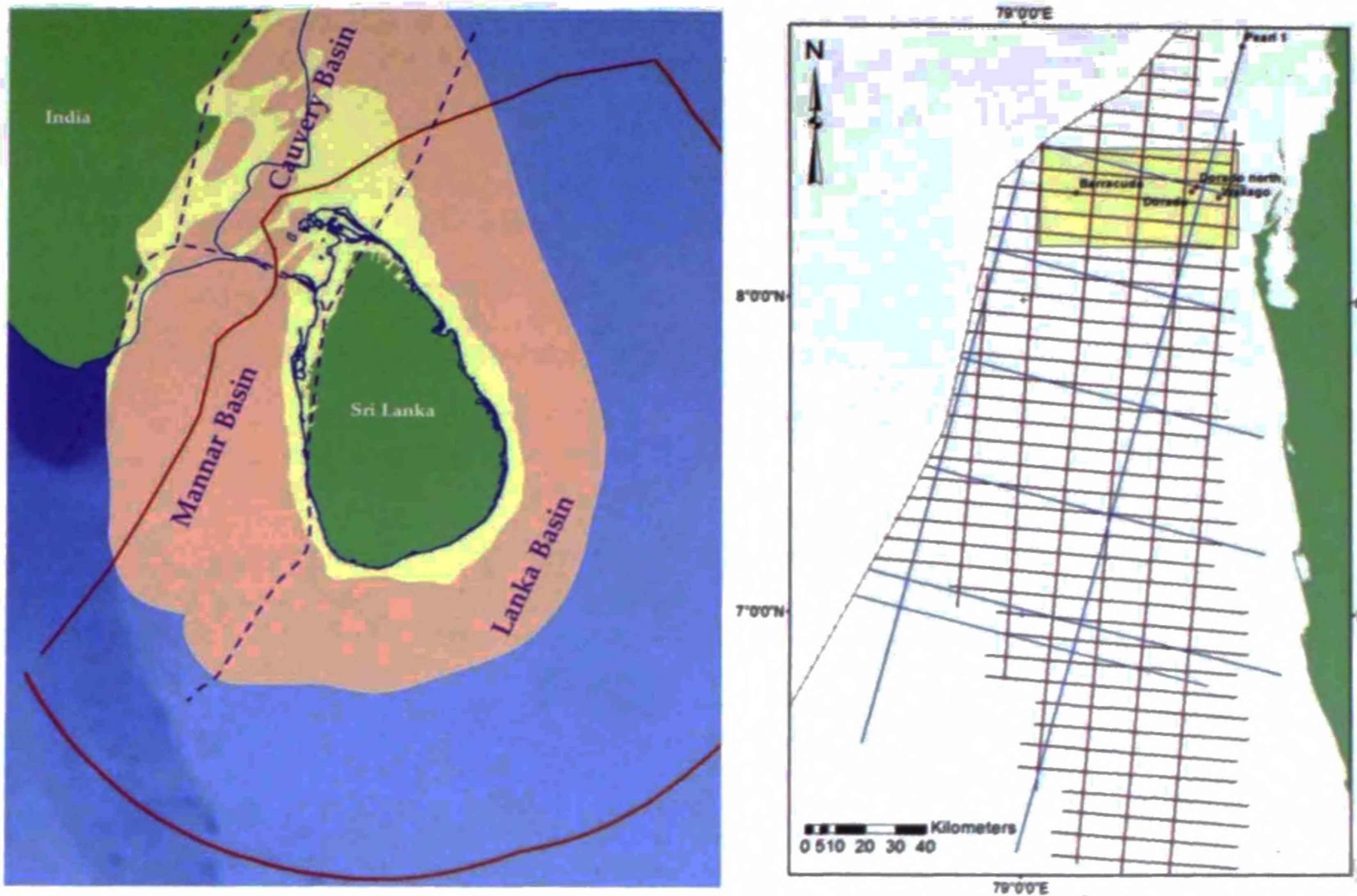

Fig. 1(a) A map showing locations of the; Mannar, Cauvery and Lanka basins. Pink colour area depicts the interpreted thick Mesozoic / Cenozoic sedimentary cover and yellow colour area depicts the thin Mesozoic / Cenozoic sedimentary cover. (b)- A map showing; Study area covering the total seismic data, 3D seismic data (yellow polygon) 2D seismic data (SL-01- blue lines & SL-05- brown lines)of the Mannar basin and well locations of Pearl 1, Dorado, Barracuda, Dorado-North, Wallago & Pearl -1

proper understanding on modes of development of such structures and their potential for the accumulation of hydrocarbon (Hansen *et al.*, 2006). Nevertheless, with the aid of 3D seismic data, there is a possibility to map forced-fold structures correctly. The growth of forced folds above sills is directly linked to the mechanical emplacement of the intrusive body and two possibilities have been proposed to describe the development of these structures.

One possible interpretation of the sill-fold relationship is that the folds form as a result of differential compaction above saucer-shaped sills (Einsele *et al.*, 1980) and the other possibility is that the folds form due to vertical displacement above saucer-shaped sills during their emplacement (Figure 2). Although the formation of structures have been studied, the relationship between sedimentary facies and forced-fold occurrence has not yet been clearly understood. This paper discusses the analyzed important factors; Timing of the forced-fold development, sedimentary facies relationship, hydrocarbon charging mechanisms and sealing potentials in detail, in order to envisage the viability of forced-folds structures as potential targets for future hydrocarbon exploitation.

TECTONIC EVOLUTION OF THE MANNAR BASIN

Mannar Basin has been evolved in four phases since Late Jurassic; Early syn-rift phase, Late syn-rift phase, Thermal sag phase and Passive margin development (Kularathna *et al.*,2015(a)). East-West Gondwana breakup was initiated approximately 165 Ma (mega annum) ago in Jurassic period (Royer *et al* .,1992). Simultaneously, Early rifting phase was initiated and resulted for the opening the Mannar basin with possible counter-clockwise rotation of Sri Lankan land mass away from greater India (Shaw, 2002).

In Early Cretaceous time, while East and West Gondwana were dispersing, Madagascar, Seychelles and Greater India were separated from Australia and Antarctica (Mizukoshi *et al.*, 1986; R. Schlich., 1982). Late syn-rift phase of the Mannar basin must have been started during

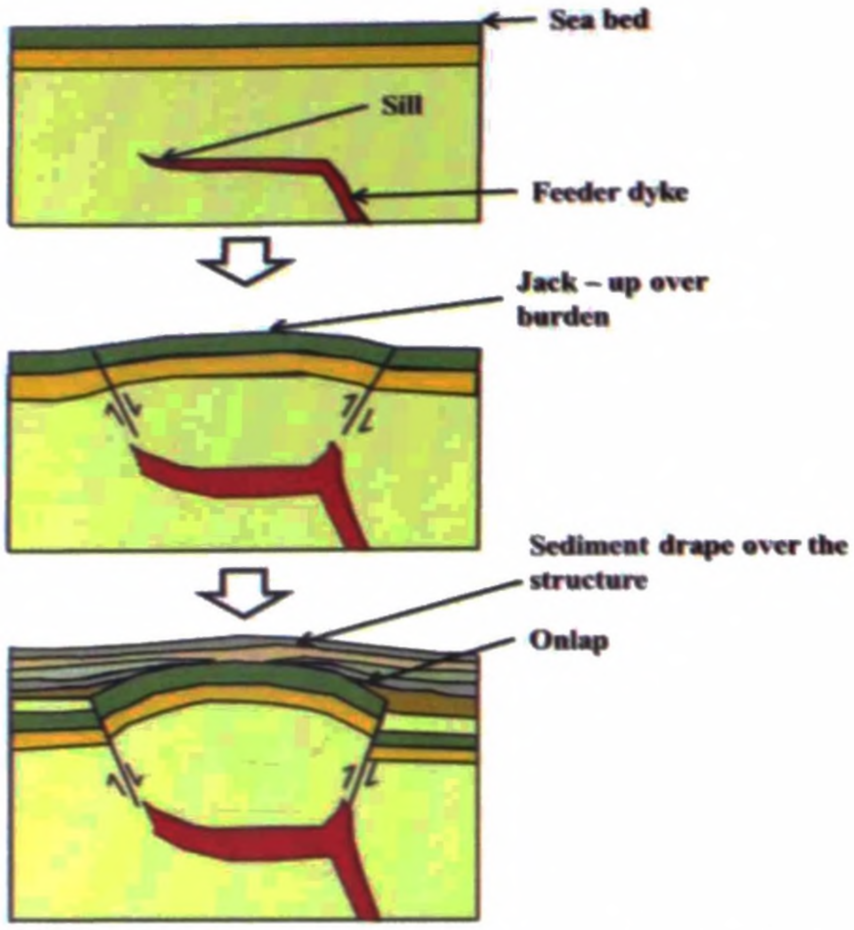

Fig. 2 Schematic illustrations of intrusion-related forced folds development by upward displacement of over burden and differential compaction

this separation. Magnetic anomaly M11 (134 Ma) recorded by Desa *et al.*, 2006 suggests that the late syn-rift phase has begun prior to this time, probably by 142 Ma. This rifting phase should be more prominent, since South to East margins of Sri Lanka assumes to be directly attached to Antarctica (Royer *et al.*, 1992). Large amount of rifting together with strike slip movement and more counter clockwise rotation caused a significant widening and rapid subsidence in the Basin. Further, it was interpreted that the formation of the Cauvery and Lanka basins was initiated during this phase (Kularathna *et al.*, 2015a). Afterwards, relative motion between Africa and Madagascar, Seychelles, India and Sri Lanka was ceased (Rabinowitz *et al.*, 1983; Cochran,1988) and rifting in the Mannar Basin was terminated. After Albian, the Post rift phase was associated with thermal sagging and passive margin development. Igneous activities such as, flood basalts and other intrusions had occurred during thermal sag phase and seem to have a connection with Deccan flood basalt, India. After, about 84 Ma, formation of Mannar basin started as a passive margin excluding the inversion during the Eocene probably associated with the Himalayan mountain belt orogeny (Kularathna *et al.*, 2015a, see Figure 3).

MATERIALS AND METHODS

Eight key horizons were interpreted for the Sri Lankan side of the Mannar Basin based on the amplitude character of the seismic data and the lithostratigraphic and chronostratigraphic information from the well reports (Ichron reports., 2012 a, b, c and d) available at Petroleum Resources Development Secretariat (PRDS). These well data guided the horizon interpretation from 3D seismic data (acquired in 2009) to the 2D seismic data set (acquired consecutively in 2001 (SL-01) and 2005 (SL-05)) (Figure 1).

Spatial occurrences of the forced-folds in the basin were interpreted and maps were generated with the aid of both 2D and 3D seismic data. Detail mapping of forced-fold structures was performed on 3D seismic data acquired in 2009. Deliberately, the forced-fold structure of Dorado gas and condensate discovery was subjected to a comprehensive study since it may provide the best information to understand the relationship between forced-fold structures and the petroleum system.

A preliminary basin modeling study was carried out for the identified and postulated source rock horizons; Z-7, Z-6, Z -5 and Z-3 (Figure 4) using Petroleum System Quick Look Plug-in (PSQL) installed on to Petrel 2011.1 software (see Table 1). Two scenarios were considered for source rock modeling. In scenario 1, same thickness of 400 m was applied for all the source rock horizons and in scenario 2, increasing thickness towards depocenter was applied. For both scenarios a generalized burial history model was applied considering high subsidence rate during the rifting phase of the basin. This Quick preliminary modeling work was performed for the identified source rocks to assess hydrocarbon generation potential of the source rock horizons above and below the Z-5 horizon. Prior to modeling interpreted time domain horizons were converted into depth domain by applying a velocity model. The velocity model was built on Petrel software using average velocities from well data as a guide for the estimation of interval velocities between horizons. Seismic interpretation, modeling and mapping were performed using the software; Petrel 2011.2.4, Kindom suite 8.3 and Arc GIS 10.1at Petroleum Resources Development Secretariat (PRDS) – data room Colombo, Sri Lanka.

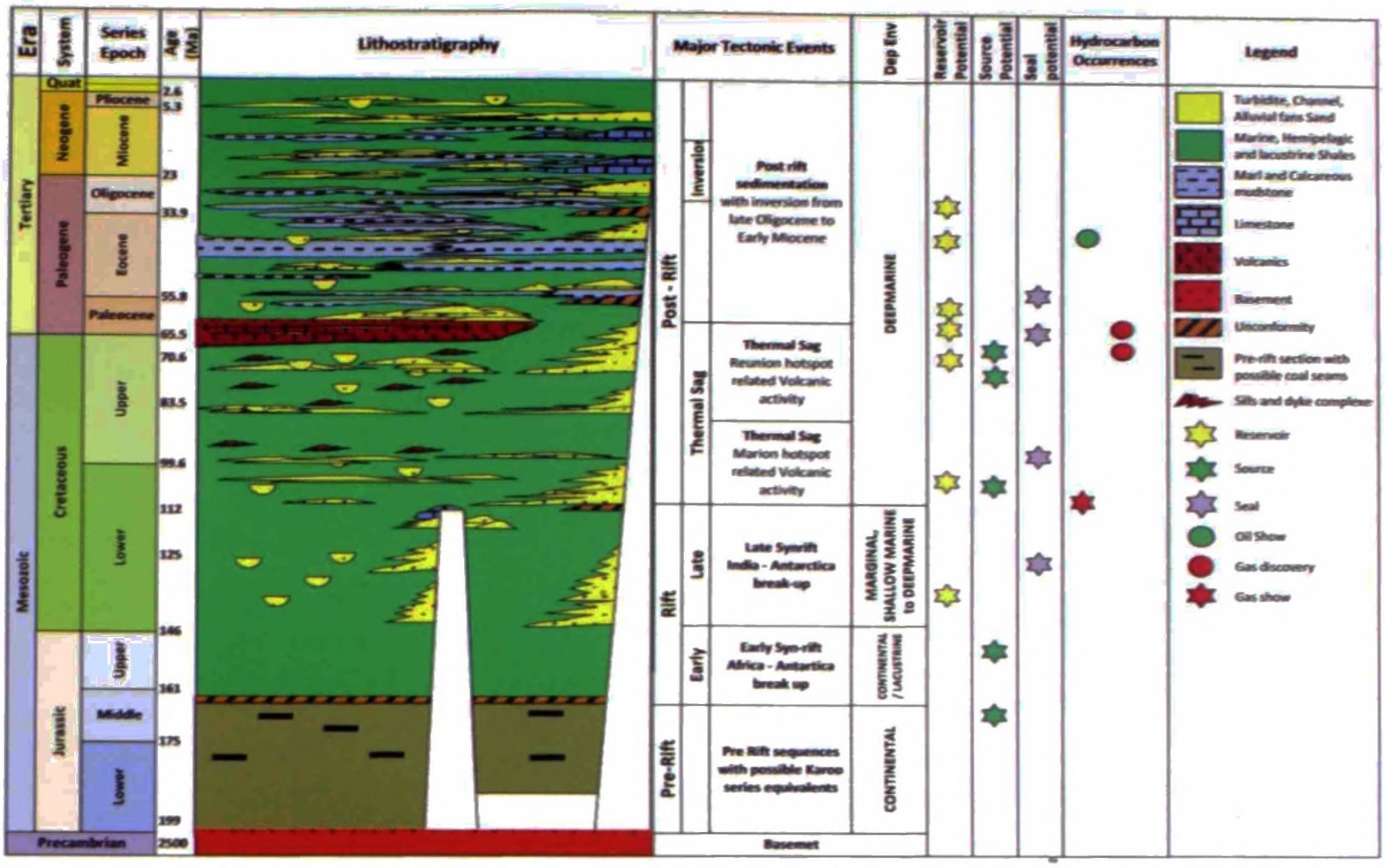

Fig. 3 Generalized stratigraphic column for the Mannar Basin (from Indian- Srilankan Maritime boundary to Sri Lanka west coast). Authors in this paper modified this stratigraphic column after shaw,2002 based on the seismic data interpretations (SL01, SL05), well data (Pearl 1, Dorado, Dorado North and Barracuda) and relevant publications (Premarathne et al., 2013; Baillie et al., 2002; Ratnayake et al., 2014; web DGH india, and Ichron, 2012(a) and Ichron,2 012 (b)). Information regarding the tectonic evolution of the Mannar Basin was extracted from the relevant publications and reports (Shaw, 2002; Kularathná et al., 2015(a); Desa et al., 2006; Ana, 2012; Royer et al., 1992; Duncan et al., 1990)

RESULTS AND DISCUSSION

Interpreted key seismic horizons are Seabed (Z-1), Oligocene top (Z-2), Eocene top (Z-3), Flood volcanic top (Z-4), Flood volcanic bottom or Cretaceous top (Z-5), Albian – Aptian top (Z-6), Late Jurassic top (Z-7) and the Basement (Z-8) (Figure 4). Horizons from Z-1 to Z-5 were guided by the well data; Dorado, Dorado North, Barracuda and Wallago. Horizons from Z-6 to Z-8 were interpreted based on the seismic amplitude character and the tectono stratigraphic framework of the basin. Horizon picking below the flood volcanic layer was problematic due to poor seismic data quality. High dense flood basalt layer has limited the penetration of seismic energies below the flood basalts and hence, the data quality is low below the Flood basalt layer (Figure 4). However, the horizon interpretation was less speculative towards the basin margin, which is not affected by flood volcanic layer.

Located forced fold structures on the seismic data can be enveloped into the sedimentary section between flood volcanic bottom (Z-5) and Albian- Aptian (Z-6) horizons (Figure 5). The present study revealed that forced folds occur in the basin as isolated ones and also as clusters. Further, it was noted that forced-fold clusters are more frequent towards the present day depocenter of the basin, whereas isolated ones are more common towards the basin margin (Figure 5). Sills, which have been intruded at levels adjacent to the Cretaceous top horizon, were resulted to develop forced-folds with high relief and those occur at deeper levels below the top Cretaceous horizon have developed forced-folds with low relief or deprived of forced-folding. It seems that the folding above sill intrusions in the Mannar basin had been governed by both upward displacement of over-burden and differential compaction as described by Hansen *et al.*, 2006. (Figures 2 and 5).

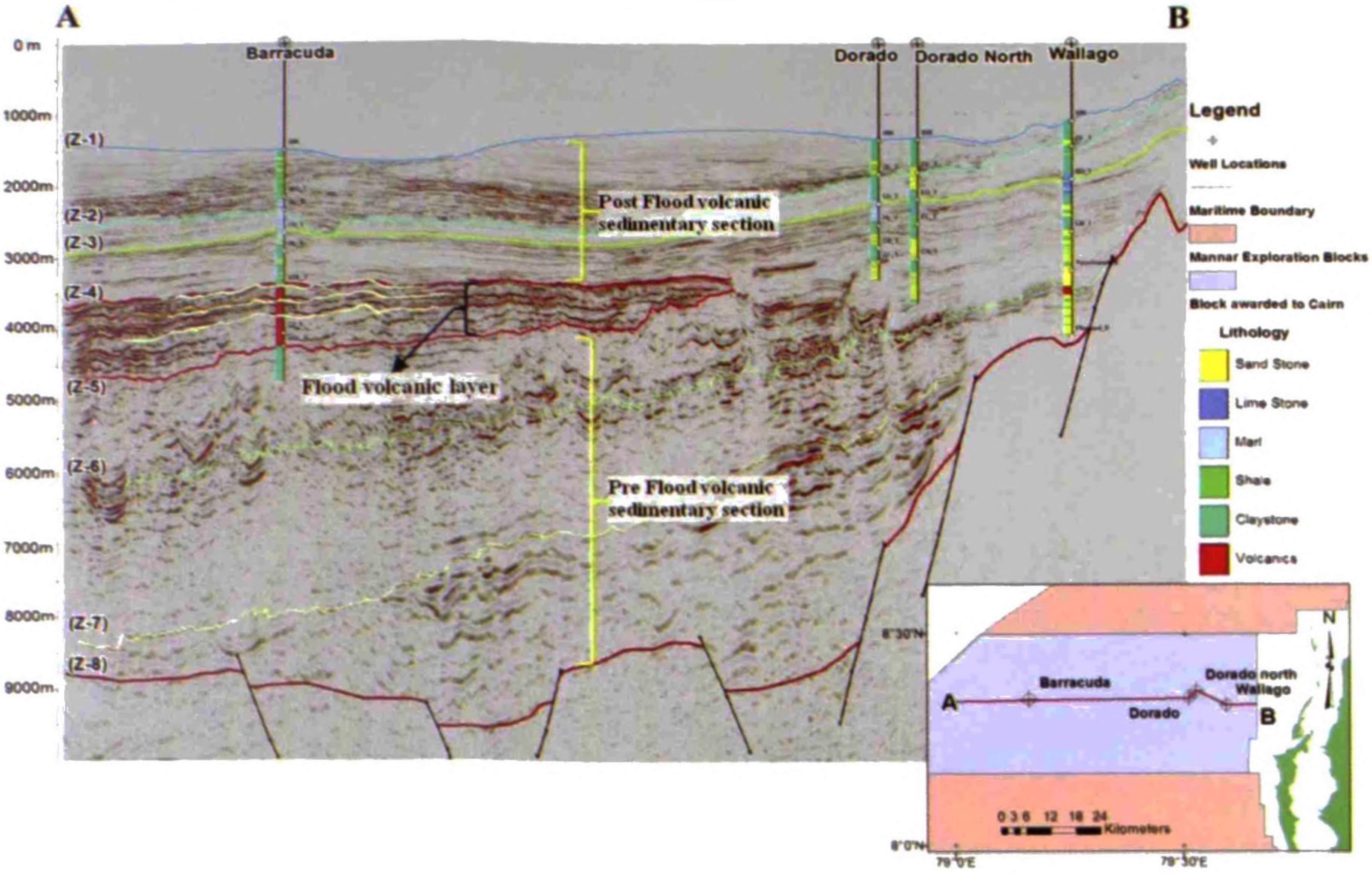

Fig. 4 A depth seismic profile through wells; Barracuda, Dorado, Dorado North and Wallago (from A-B in the base map). It illustrates the litho stratigraphy along the wells and major structural elements in the basement with interpreted key horizons. Note that the quality of the seismic data is very poor below the flood volcanic layer (pre-flood volcanic sedimentary section)

Forced-fold structure, which was penetrated by the well Dorado, provides detail lithology of the top most part of the structure. The top part of the structure is comprised of predominantly claystone with minor sandstone and marl layers. Layers below the top part are predominantly sandstone with relatively thin shale, claystone and marl layers. However, this well has not completely penetrated this structure to the level of sill-intrusion. This structure has an average vertical relief of approximately 180 m and an aerial extent of approximately 9 km^2. The structure is a four way dip closure that is formed by folding accompanying with set of reverse faults (Figure 6).

Well correlation from Dorado to Dorado – North and the seismic profile through these wells show that the same sedimentary sequence has been displaced by a reverse fault. Therefore, it is indicated that the structure development had been mainly governed by upward displacement by the sill intrusion (Figure 6). Further, well data show that the sedimentary section below the top of the forced-folded structure is predominated in sandstone with minor clay stone, marl and shale. This indicates that the forced fold might have been developed in sandstone dominated sedimentary facies of the basin. However, this process needs to be further understood in detail.

Shallow level sill intrusions can produce significant folding of the contemporaneous sea bed (Hansen *et al.*, 2006). Cretaceous top horizon shows significant folding caused by igneous intrusions and folding due to intrusions is not visible in the sedimentary sections above the Cretaceous top horizon. Therefore, it can be assumed that forced folds in the basin should have been occurred during the late cretaceous, probably during Maastrichtian (~66 Ma). The Reunion hotspot began with a rapid eruption of massive volumes of the Deccan flood basalts approximately 65 Ma ago (Duncan,1990) and thus sills must have been fed by the Reunion hotspot. Further, the tectonostratigraphic evolution of the Mannar basin, the sedimentary

Table 1 A summary of the input parameters for source rock modeling

Source rock Horizon	Upper Jurassic source horizon (Z-7)	Upper Jurassic source horizon (Z-7)	Albian – Aptian source horizon (Z-6)	Campanian – Maastrichtian source horizon (Z-5)	Eocene source horizon (Z-3)
Thickness	400m / increases towards the depocenter of the basin	400m / increases towards the depocenter of the basin	400m / increases towards the depocenter of the basin	400m / increases towards the depocenter of the basin	400m / increases towards the depocenter of the basin
Age (Ma)	145	145	100	65	33
Kerogen type	I	III	II	II	II
TOC (Total Organic Carbon)	1	1	1	1	1
HI (Hydrogen Index)	500	300	500	500	500
Seabed Temp (K)	278.55K	278.55K	278.55K	278.55K	278.55K
Thermal Gradient (top Boundary condition) ^{0}C/km	42	42	42	42	42
Expulsion method	Pepper Adsorption	Pepper Adsorption	Pepper Adsorption	Pepper Adsorption	Pepper Adsorption
Age filter (Ma)	65-0	65-0	65-0	65-0	33-0

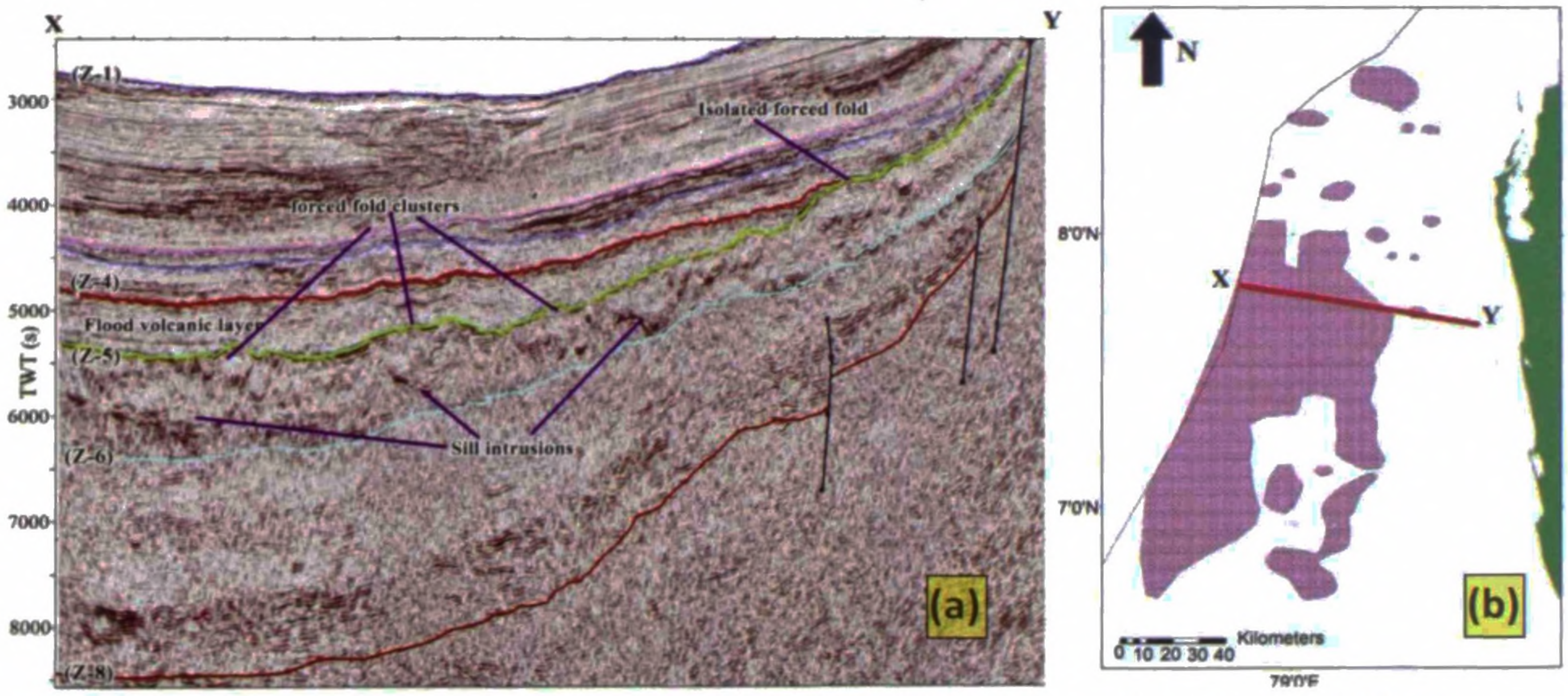

Fig. 5 (a) Time seismic section showing; sill intrusions, flood volcanic layer, forced-fold clusters, isolated forced folds and the horizons.Top Cretaceous horizon (Z-5) shows clear folding above the sill intrusion and the forced fold structures are enveloped between the horizons Z-5 and Z-6 (b) Base map showing the location of seismic section "(a)" and the distribution of forced-fold structures (in pink colour pattern). Forced-folds are more frequent towards the depocenter of the basin

section with forced-folds has been developed during the thermal sag phase in the post rift stage. After Paleocene age (~55Ma) these forced-fold structures should be equipped for hydrocarbon accumulation, if trapping conditions are available. Basin modeling results suggest that the main potential source rock intervals (Shaw, 2002) present in the Mesozoic section has generated significant volumes of oil and gas after 55 Ma to charge the forced-folds (Figures 8 and 9).

Areas with a high density of intruded shallow level sills have formed many forced-folds at the

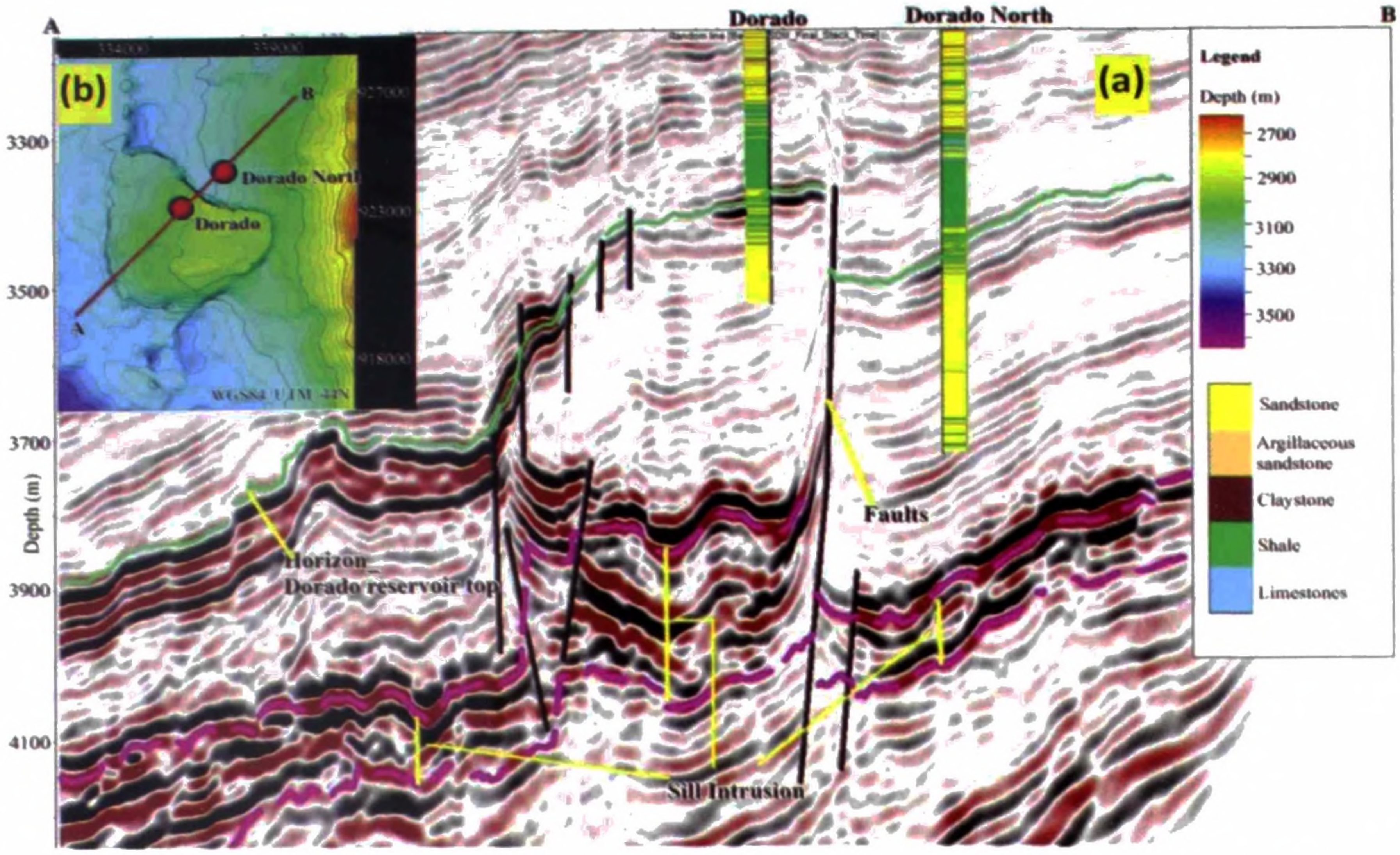

Fig. 6 (a) Depth seismic section through wells; Dorado and Dorado North (A-B) showing the Dorado forced-fold structure and generalize lithology of Dorado and Dorado North. The structure is bounded by set of reverse faults and in the crest several normal and reverse faulting can be identified (b) A depth map showing the top of the forced fold structure

same location, which are known as forced-fold clusters. The clusters are comprised with many forced-folds, which have generated large scale dome like structures with significant vertical relief over a large area (Figure 5). Therefore, these areas could offer regional scale dip and fault bounded closures for large volumes of hydrocarbon accumulations.

Forced-folding at the top Cretaceous horizon is more frequent in the Mannar Basin and an extrusive flood volcanic layer covering more than two third of the area in the Sri Lankan jurisdiction of the Mannar Basin exists just above the top Cretaceous horizon (Figures 4 and 5). Barracuda gas discovery in the basin has proven that the flood volcanic layer has a very high sealing capacity (Kularathna *et al.*, 2015(b)). Therefore, the flood volcanic layer can act as a regional seal above the top cretaceous horizon. However, faulted areas of the flood volcanic layer could reduce its sealing capacity by providing migration paths to the sedimentary sequences above flood volcanic layer.

Basin modeling was performed by PSQL – plug-in. Although this plug-in is not an advance basin modeling software, it is capable of providing preliminary 3D basin modeling results. The 2-component kinetic model defined by Pepper and Corvi, 1995 is used in the PSQL plug-in for Type I, II and III kerogen and the kinetic information has been lab tested taking different samples from different marine siliciclastic basin. Since late synrift Mannar basin's depositional environments is mainly marine and the data availability is limited so that, this plug-in is capable of providing reasonably satisfactory results.

Considering the paleo-depositional environments (Figure 3) possible kerogen types were determined. During upper Jurassic or in Early syn rift phase a continental to lacustrine environment has been interpreted, thus type III source rock can be anticipated (Peters, *et al* ., 2007). Albian –Aptian time major area of the basin has been in a deep marine depositional environment and, thus type II source rock can be expected (Peters, *et al.*, 2007). Pesalai-1 well has penetrated an approximately 300 m thick type II oil prone source rock provides evidence regarding the possibility of existence type II in the basin (Cernock, 1976). Throughout Campanian to Maastrichtian time the major part of the Mannar Basin was at a deep marine

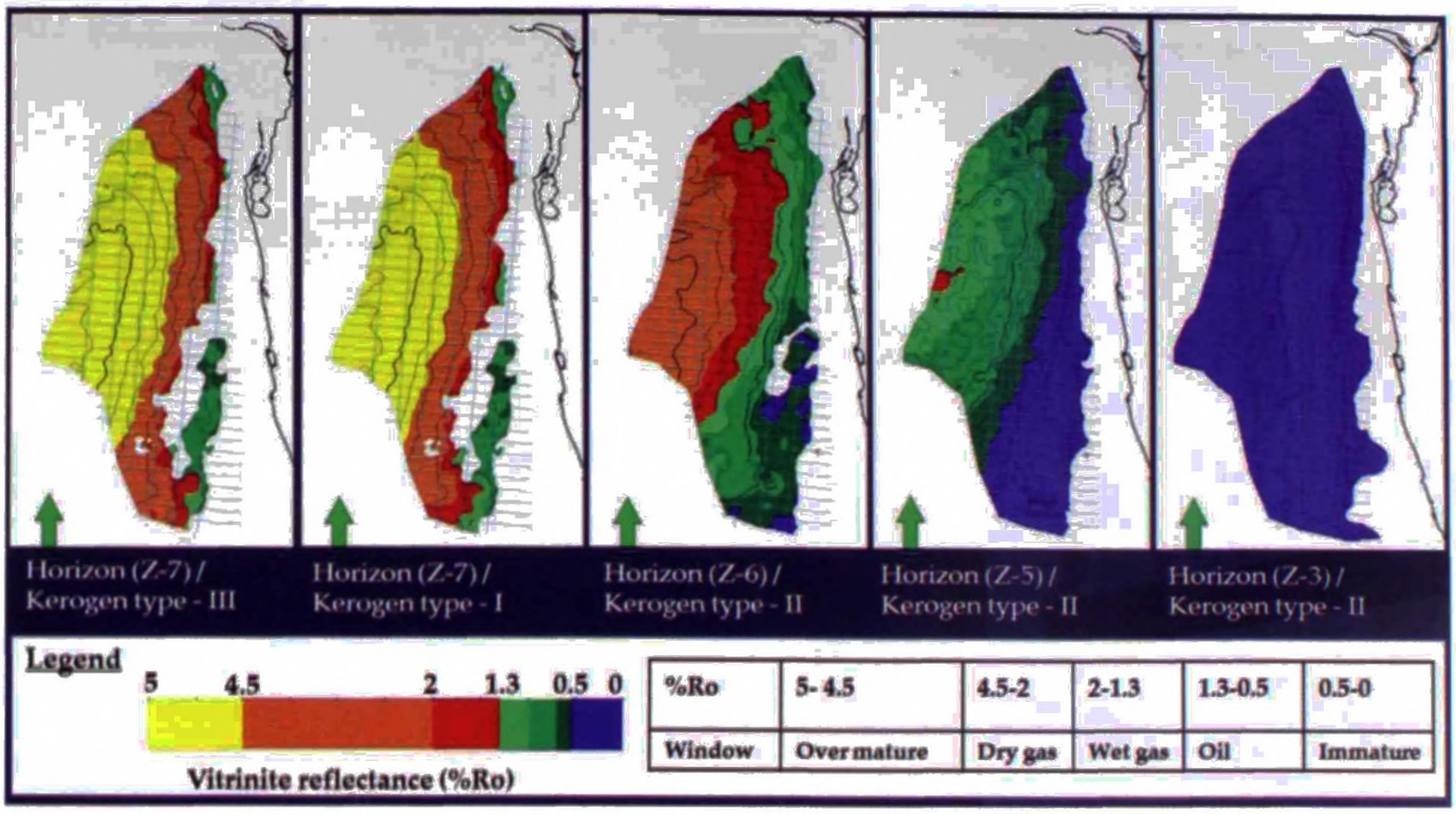

Fig. 7 Maturity maps of source rock horizons; Z-7, Z-6, Z-5 and Z-3. Yellow colour (%Ro 5-4.5) indicates the over mature window, brownish orange colour (%Ro 4.5-2) indicates the dry gas window, red colour (%Ro 1-1.3) indicates the wet gas window, light to dark green colour (%Ro 1.3-0.5) indicates the oil window and blue colour (%Ro 0.5-0) indicates the immature window. Contour interval is 500 m

setting, thus type II is the most possible. Ichron limited., 2012 (a,b andc) reports prove the existence of type II marine shale source rocks. The basin was at a deep marine setting during Eocene period and, therefore type II was anticipated. Same TOC value was considered for all the source rocks horizons. Generalized HI values were considered for the source rocks; High HI values for type II and low HI values for type III (Peper and Dodd, 1995). Average seabed temperatures and average thermal gradients were obtained based on the data from Ichron limited., 2012 (a, b and c) reports.

Despite the generated hydrocarbon volumes, both the scenarios of the basin modeling, have delivered similar results. The output of results pertaining to scenario 1 is shown in figures 7, 8, and 9. Obtained maturity maps (Figure 7) were validated with the vitrinite reflectance data from the geochemical reports available at PRDS (Ichron limited., 2012 (a,b and c)). Since the wells in the Mannar basin have not been drilled beyond Campanian – Maastrichtian sequences, above validation is able to be performed only for the younger horizons (Z-3 & Z-5) that are present above the Campanian – Maastrichtian only. The modeled maturity data for the horizons; Z-3 and Z-5 are strongly comparable with the maturity indices presented in the geochemical reports (Ichron limited.,2012 (a,b,c)). Therefore, the rest of the modeled maturity data for the horizons; Z-7 and Z-6 were anticipated as valid information and also it was assumed for generation models.

The basin modeling results show that the major portion of the Z-7 horizon is over mature for hydrocarbon generation. Geological time from 65 Ma to 0 Ma (recent) oil expulsion has been occurred in the basin margin and, gas generation has been occurred in the central part of the basin. Major portion around the present day depocenter of the Z-6 horizon is at the dry gas window. From 65 Ma to 0 Ma (Recent age), oil expulsion has been concentrated into the basin margin, whereas gas generation has been concentrated to the center area of the basin. For the time period of 65 Ma to 0 Ma, both Z-7 and Z-6 horizons have generated higher gas volumes than oil. Major portion around the present day depocenter of the Z-5 horizon is mainly at an oil window and a narrow region towards the basin margins is immature. From 65 Ma to 0 Ma both oil and gas expulsion has been taken place from the center area of the basin and comparatively higher oil volumes have been generated. Z-3 horizon is predominantly immature and it has not expelled hydrocarbon (Figures 7, 8 and 9).

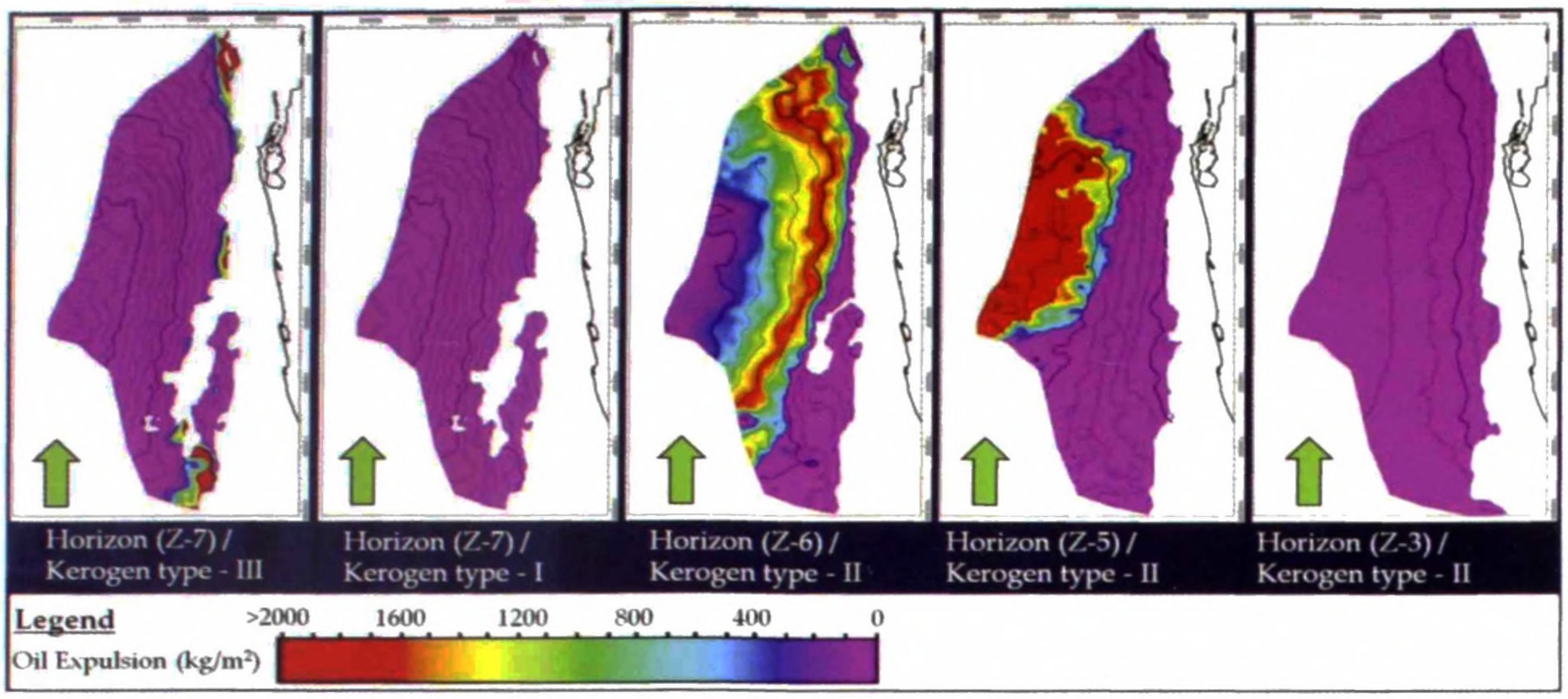

Fig. 8 Oil expulsion maps of source rock horizons Z-7, Z-6, Z-5 and Z-3 for the time period from 65Ma to 0Ma. Oil volumes expelled is indicated from higher (red colour) to lower (magenta colour) represented by template Rainbow colour bar. Contour interval is 500 m

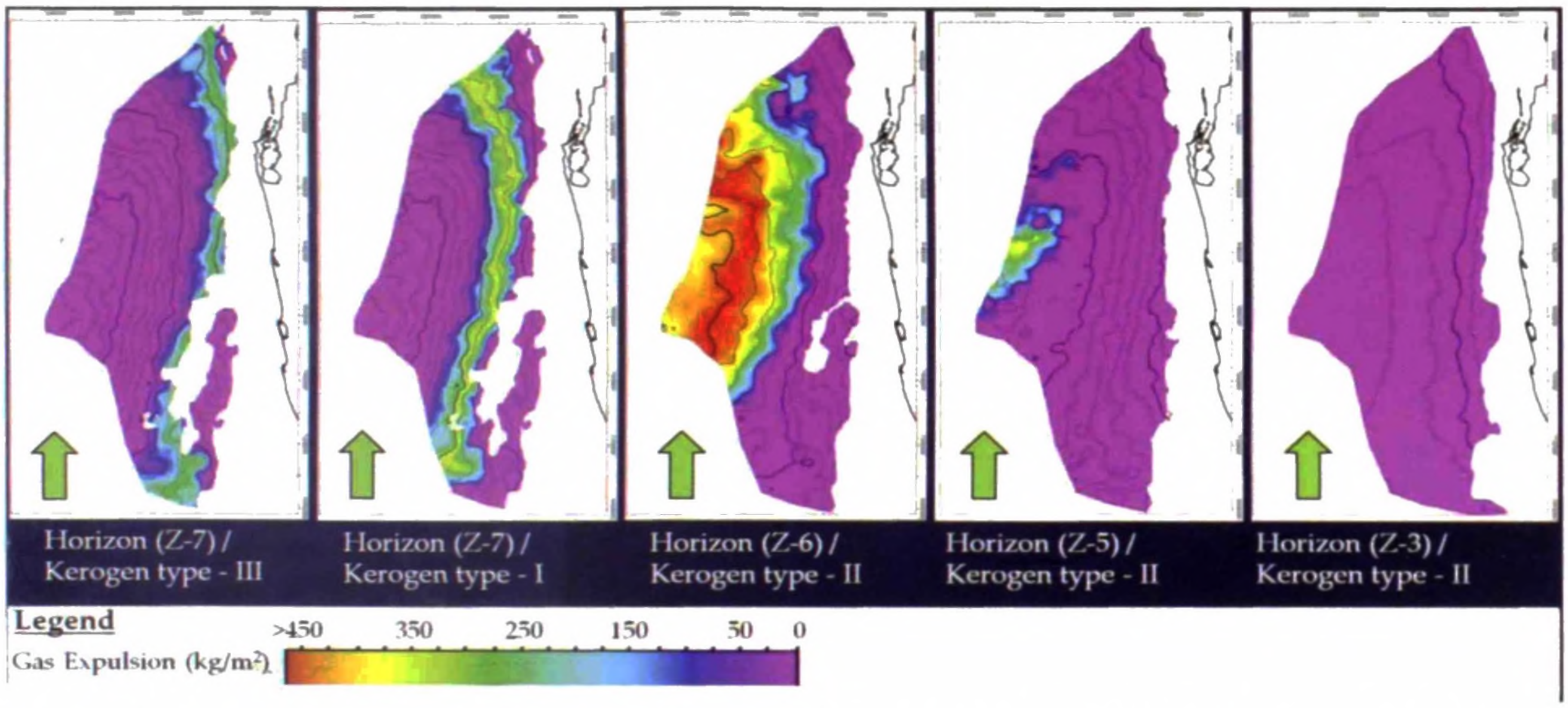

Fig. 9 Gas expulsion maps of source rock horizons Z-7, Z-6, Z-5 and Z-3 for the time period from 65Ma to 0Ma. Gas volumes expelled is indicated from higher (red colour) to lower (magenta colour) represented by template Rainbow colour bar. Contour interval is 500 m

The results of overall basin modeling show that horizons; Z – 7, Z – 6 and Z – 5 have generated significant volumes of both gas and oil. Therefore enough charging is possible for forced folds in the presence of source rocks below the above horizons. Uncertainties involving in velocity modeling, seismic interpretations and basin modeling may modify the modeling results.

CONCLUSIONS

Igneous activities occurred during Maastrichtian may have resulted in the formation of forced fold structures in the basin. Isolated and clusters of forced fold structures have generated small to larger scale folding at the top Cretaceous horizon. The clusters of forced fold structures are common towards the present day depocenter of the basin and isolated structures are commonly located in the margins of the basin. These structures may be predominated in the sandstones. Further, the basin modeling reveals the possibility for the generation of significant amounts of gas and oil below top Cretaceous horizon. Existence of proven mature source rocks below the top Cretaceous horizon and proven sealing capacity of the flood volcanic layer just above the top Cretaceous horizon indicate high potential for hydrocarbon accumulation in isolated and clusters of forced-fold structures. These structures may be potential targets for future hydrocarbon exploration activities in the Mannar basin.

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