Why classical sequence stratigraphy doesn't work in Pannonian basin?

Dejan Radivojević

ZAŠTO KLASIČNA SEKVENCIONA STRATIGRAFIJA NE FUNKCIONIŠE U PANONSKOM BASENU?

Dejan Radivojević[1]

[1)] Univerzitet u Beogradu, Rudarsko-geološki fakultet, Departman za regionalnu geologiju,
Kamenička 6, 11000 Beograd, e-mail: dejan.radivojevic@rgf.bg.ac.rs

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UVOD

Prvobitna klasična sekvenciona stratigrafija je napravljena za modele pasivnih margina (e.g., Vail et al., 1977; van Wagoner et al., 1990) gde su brzina i promena tektonskog tonjenja male u poređenju sa aktivnim riftnim basenima ili područjima iza ostrvskog luka (Prosser, 1993; Nottvedt et al., 1995; Martins-Neto and Catuneanu, 2010). Ovaj koncept je u poslednjih dvadeset godina znatno evoluirao tako da je formiran sekvenciono stratigrafski model za riftne basene (Weimer & Posamentier, 1993; Loucks & Sarg, 1993; Emery & Myers, 1996; Posamentier & Allen, 1999; Catuneanu, 2002, 2006; Catuneanu et al., 2009; Martins-Neto & Catuneanu, 2010).

Panonski basen predstavlja basen iza ostrvskog luka sa veoma intenzivnom i mladom tektonikom.

Pored toga u jezeru Panon (Magyar et al., 1999) nisu razvijene sve klasične sekvence. U njemu nedostaju elementi koji bi ukazali na veliki pad jezerskog nivoa kao i depozicioni oblici karakteristični za nizak nivo jezera. Relativni nivo jezera Panon koji se nalazi u konstantnom izdizanju ili mirovanju zajedno sa visokim nivoom sedimentacije doveo je deponovanja agradacionih do progradacionih sekvenci.

MATERIJAL I METODE

U svrhu određivanja promene osnovnog nivoa (*base level*), tektonskih i sedimentacionih odnosa urađen je regionalni seizmički kompozitni profil (slika 1) dužine preko 260 km na kome je demonstrirana primena sekvencione stratigrafije riftnog basena. Profil pokriva ceo srpski deo Panonskog basena, od srpsko-mađarske granice do ulaska Dunava u Karpate. Prilikom interpretacije seizmičkog profila korišćeni su podaci dobijeni istražnim bušenjem naftnih bušotina i dodatni seizmički profili. Interpretacija je obuhvatala određivanje vremena riftogeneze, depozicionih sredina (Prosser, 1993), izdvajanja tektonskih sistemskih pojaseva (*tectonic system tract*) i analizu promene osnovnog nivoa.

RIFTNA SEKVENCIONA STRATIGRAFIJA REGIONALNOG GEOLOŠKOG PROFILA

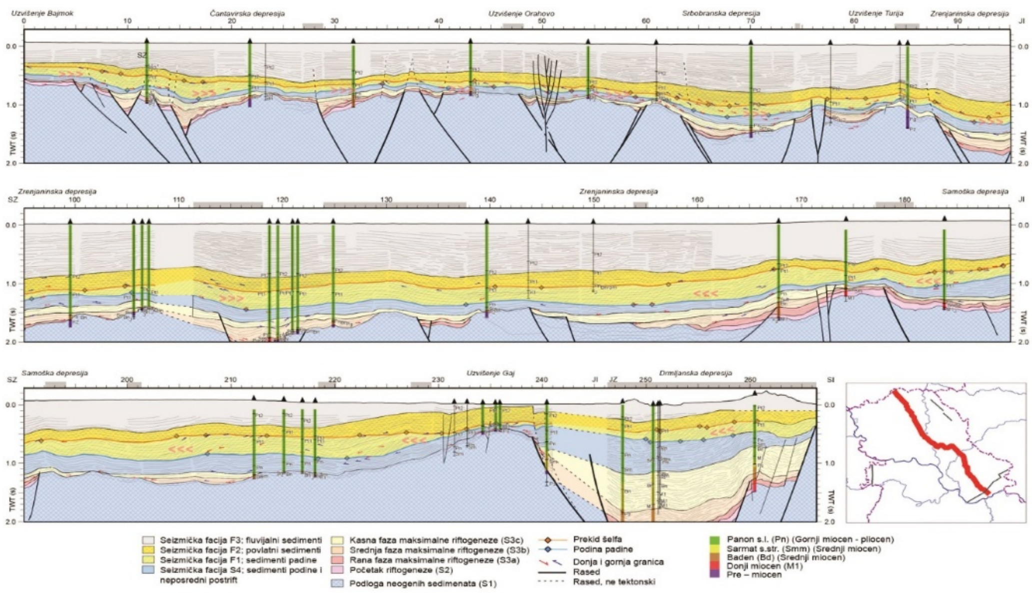
Neki autori smatraju da je početak riftogeneze u Panonskom basenu označen brzim tonjenjem i formiranjem velikog prostora za akumulaciju sedimenata dok drugi zastupaju mišljenje o laganom režimu tonjenja usled kojeg dolazi do formiranja malog prostora za akumulaciju sedimenata.

Usled asimetrije polugrabena i njihovog tonjenja koje je kontrolisano jednim glavnim rasedom, stvaranje prostora za zapunjavanje sedimentima u riftnim basenima je promenljivo. Iz tih razloga tradicionalni (klasični) pristup sekvencione stratigrafije je neprimenljiv. Razumevanje ovog sistema je važno u smislu formiranja tektonski i klimatski kontrolisanih riftnih ciklusa.

Interpretacijom tektonskih sistemskih pojaseva i korelacijom sa bušotinskim podacima, jasno se uočava da je ekstenzija dijahrona i da se faktor istezanja znatno menjao duž regionalnog profila. Neka područja pretrpela su ekstenziju slabijeg intenziteta, dok su druga pretrpela višefaznu riftogenezu. Najstariji sistem faze maksimalne riftogeneze je donjomiocenske starosti, dok je najmlađi donjopontski (Matenco and Radivojević, 2012).

Iznad preriftne sekvence (S1) nalazi se sistemski pojas početka riftogeneze (S2), koji je čest u dubljim delovima (polu)grabena. Sekvence generalno imaju klinoliku geometriju, s tanjim delom klina na podinskom bloku raseda i većom debljinom sedimenata na samom rasedu. Seizmički zapis unutar sekvence obično je loš, a na mestima gde je prisutan ima brežuljkastu geometriju u blizini raseda. Ovaj sistemski pojas nije utvrđen na svim (polu)grabenima i može biti povezan s trenutkom početka riftogeneze u određenom grabenu. On suštinski predstavlja sistemski pojas početka riftogeneze formiran u kontinentalnoj/aluvijalnoj sredini (Prosser, 1993). Iz tih razloga, u slučaju da je proces riftogeneze počeo u trenutku kada je ovaj region već „potopljen“, ovaj sistemski pojas je veoma teško razdvojiti od sistemskog pojasa faze rane maksimalne riftogeneze.

Osim sistemskog pojasa početka riftogeneze, izdvojeni su rani (S3a), srednji (S3b) i kasni (S3c) sistemski pojas maksimalne riftogeneze. U grabenima sa manjim tonjenjem, jedan ili više ovih sistemskih pojaseva može izostati. Oni se verovatno nalaze ispod nivoa seizmičke rezolucije, tako da njihovo izdvajanje nije bilo moguće. Sistemski pojas rane maksimalne riftogeneze obično se završava progradacionim rubom (*downlap*) na pretercijarne formacije ili na sistemski pojas početne riftogeneze. Sedimenti rane maksimalne riftogeneze obično su prisutni samo u dubljim delovima grabena. Razlozi njihovog odsustva jesu to što graben još nije dostigao svoju konačnu veličinu u trenutku depozicije i što je brzina tonjenja znatno veća od agradacije. Od tri sistemska pojasa faze maksimalne riftogeneze, rani obično ima najtanje sedimente. U velikim grabenima, izgled seizmičkih refleksija često je divergentan u pravcu rasedne površine tako da one imaju oblik klina. Usled aktivnog rasedanja sedimenti su često veoma iskošeni. Sistemski pojas faze kasne maksimalne riftogeneze (S3c) razlikuje se od pojasa faze srednje maksimalne riftogeneze (slika 1) po širenju sedimentacije na (često delimično erodovan) podinski blok. Pored toga, u sistemskom pojasu faze kasne maksimalne riftogeneze iskošavanje sedimenata je manje nego ranije i sedimenti zapunjavaju veći deo preostalog prostora za deponovanje.



Slika 1. Regionalni geološki profil kroz srpski deo Panonskog basena (ter Borgh et al, 2015).
Figure 1. Regional geological transect from Serbian part of Pannonian basin (ter Borgh et al, 2015).

Postriftni tercijarni sedimenti predstavljeni su progradirajućim deltnim sistemom. Na slici 1, označene su facije donjeg (*bottomsets*, S4), prednjeg (*foresets*, F1) i gornjeg dela delte (*topsets,* F2). Facije S4 i F1 razdvojene su donjim delom padine (*base of slope*), a F1 i F2 prekidom šelfa (*shelf break*). U postriftnim tercijarnim sedimentima identifikovane su brojne sekvence. Prva (P1) ima gotovo uniformnu debljinu duž profila, sa izuzetkom krajnjeg jugoistočnog dela u blizini Karpata, gde je njegova debljina veća (slika 1). Reflektori u ovoj jedinici uglavnom su paralelni i kontinuirani i predstavljeni dubokovodnim sedimentima. Druga sekvenca (P2) razlikuje se od povlatnih jedinica po unutrašnjoj konfiguraciji refleksija. Progradacija ide od oboda profila ka njegovom centru, koji se nalazi između 65 i 160 km na regionalnom profilu (slika 1). Progradaciona sekvenca može biti korelisana sa formacijama padine i turbiditnih jezerskih tokova koji su definisani u severozapadnim delovima Panonskog basena (Juhasz *et al.,* 2007, Sztano et al., 2016, Ivanišević & Radivojević, 2018). Treća sekvenca (P3) prisutna je samo u najdubljim centralnim delovima regionalnog profila, između 63 i 76 km, i 90 i 165 km u zrenjaninskoj depresiji (slika 1). Reflektori koji progradiraju u pravcu jugoistoka, između 0 i 120 km uglavnom su dobro definisani, dok je na oko 120 km prisutna grupa haotičnih refleksija. Ove refleksije, koju su formirane uz normalni rased, verovatno vode poreklo od masivnih tokova (*mass flow*).

Refleksije progradacionih serija u pravcu severozapada slabije su definisane i više haotične usled smetnji u seizmičkom zapisu. Sekvenca P3 takođe se može korelisati sa prethodno pomenutim formacijama. Podloga završne sekvence (P4) uglavnom se sastoji od kontinuiranih refleksija velike frekvencije. Za razliku od podinskih jedinica, u ovoj sekvenci nije prisutna progradacija, dok seizmičke refleksije u pravcu povlate postaju više diskontinuirane. Donji deo sekvence može biti korelisan sa formacijom deltnih i priobalnih sedimenata, dok gornji deo odgovara formaciji fluvijalnih sedimenata.

WHY CLASSICAL SEQUENCE STRATIGRAPHY DOESN'T WORK IN PANNONIAN BASIN?

Dejan Radivojević[1]

[1)] University of Belgrade, Faculty of Mining and Geology, Department of Regional Geology, Kamenička 6, 11000 Belgrade, e-mail: dejan.radivojevic@rgf.bg.ac.rs

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INTRODUCTION

Classical sequence stratigraphy has been developed in passive-margin settings (e.g., Vail et al., 1977; van Wagoner, 1990), where the rates and variability of tectonic subsidence is minor in comparison with active rift basins or in back-arc areas (e.g., Prosser, 1993; Nottvedt et al., 1995; Martins-Neto and Catuneanu, 2010). This concept significantly evolved in last twenty years, so the rift sequence stratigraphy model was made (Weimer & Posamentier, 1993; Loucks & Sarg, 1993; Emery & Myers, 1996; Posamentier & Allen, 1999; Catuneanu, 2002, 2006; Catuneanu et al., 2009; Martins-Neto & Catuneanu, 2010).

The Pannonian basin is back-arc basin with very intensive and young tectonic. Besides that, in the Lake Pannon (Magyar et al., 1999) no traditional sequences were developed. There is the lack of the elements which will point to significant lake level drop as well as the depositional features characteristic for low lake water level. Relative Lake Pannon water level which is in constant rise or stand combined with high sedimentation rate led to deposition of aggradational to progradational sequences.

MATERIAL AND METHODS

The regional composite seismic transect (figure 1) with length of more than 260 km at which rift sequence stratigraphy method is demonstrated is made to determine the range of base level change, as well as tectonic and sedimentary relationships. The transect covers entire Serbian part of Pannonian basin from Serbia-Hungary border to Danube entrance into Carpathians. Exploration well data and additional seismic lines were used during the transect interpretation. The interpretation included determination of rift timing, depositional environments (Prosser, 1993), tectonic system tract separation and base level changes analysis.

RIFT SEQUENCE STRATIGRAPHY OF REGIONAL GEOLOGICAL TRANSECT

Some authors consider that the Pannonian basin rift initiation is marked with fast subsidence and creation of large accommodation space, while others advocate slow subsidence regime which formed small accommodation space. Because of half-graben asymmetry and subsidence is controlled by one major fault, accomodation space in rift basins is variable. From those reasons traditional sequence stratigraphy approach is not applicable. This understanding is important in the context of the formation of tectonically and climatically controlled rift cycles.

With interpretation of tectonic systems tract and well data correlation one can clearly notice that extension is diachron and that stretching factor change along regional transect. Some areas experienced extension of lower intensity while others passed through the multi-phase rifting. The oldest rift climax phase is of Early Miocene, while youngest is Early Pontian (Matenco and Radivojević, 2012).

Above pre-rift sequence (S1) there is rift initiation system tract (S2) which is common in deeper part of half-graben. Generally, sequences had wedge shape geometry, with thinner part at the hanging wall and greater thickness at the fault itself. Usually seismic record within sequence is poor, while at some places close to the fault it has hummocky geometry. This systems tract is not confirmed in all half-graben and could be related to the moment of initial rifting in certain graben. Essentially it represents initial rifting systems tract formed in continental/alluvial environment (Prosser, 1993). From those reasons, in case that rifting process started in moment when area was already flooded this systems tract is very hard to distinguished from early rift climax systems tract.

Besides initial rift systems tract also early (S3a), middle (S3b) and late (S3c) rift climax systems tract is alinated. In grabens with low subsidence, one or more of that systems tract could be absent. They are probably below seismic resolution level, so their recognition was not possible. The early rift climax systems tract usually ends up with downlap on pre-Tertiary formations or on the initial rift systems tract. Early rift climax sediments are usually present only in deep parts of the basin. The reasons for their absence are that graben haven't reach its final size in the moment of deposition and the subsidence rate is much lower than aggradation. From three rift climax systems tract the early one usually has thinnest sediments. In big grabens, seismic reflections appearance is frequently divergent toward fault plane so they have wedge shape. Because of active faulting sediments are frequently tilted. The late rift climax systems tract (S3c) differ from middle rift systems tract (figure 1) since its sediments expand to footwall block (frequently is partly eroded). Besides that, in late rift climax systems tract sediments dipping is less than earlier and sediments filled the biggest part of the rest of accommodation space.

The postrift Tertiary sediments are represented with prograding delta system. The delta bottomsets (S4), foresets (F1) and topsets (F2) facies are marked at figure 1. The facies S4 and F1 are separated with base of slope, while F1 and F2 are marked by shelf break. Within postrift Tertiary sediments numerous sequences are recognized. The first one (P1) has almost uniform thickness across the transect with exception in southeastern end in vicinity of Carpathians where its thickness is higher (figure 1). Seismic reflections within this unit are mostly parallel and continuous and represented with deep-water sediments. Second sequence (P2) differ from overlying units because of its internal reflection configuretion. Progradation goes from the edge toward the center, which is between 65 and 160 km at regional transect (figure 1). Progradational sequence could be correlate with slope and turbidite flow formations which were defined in northwestern part of Pannonian basin (Juhasz *et al.,* 2007, Sztano et al., 2016, Ivanišević & Radivojević, 2018). The third sequence (P3) is present only in deepest central part of regionnal transect, between 63 and 76 km, and 90 and 165 km in Zrenjanin Depression. Reflections which are prograding toward southeast, between 0 and 120 are mostly well defined, while at around 120 km the chaotic group of reflections are present. These reflections were formed along the normal fault and probably originate from mass flow. The series of progradational reflections toward northwest are not that well defined because of interference in seismic record. The sequence P3 could also be correlated with previously mentioned formations. The base of final sequence (P4) is mostly made of continuous high frequency reflections. Unlike bottom units in this sequence there is no progradation present, while the seismic reflections toward top become more discontinuous. The lower sequence part could be correlated with delta and coastal sediments, where the upper part corresponds to fluvial sediments formation.

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