Thermal anomalies, updoming and non-marine sequence stratigraphy: a case history from the Karoo Basin, South Africa

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Introduction

The Karoo Basin is one of the most extensively exposed and well studied of all the major Gondwana basins along the southern margin of Gondwana. It has been modelled as a retro-arc foreland basin in which the basin-fill has been divided into 1st, 2nd and 3rd order depositional sequences, bounded by unconformities and/or abrupt facies changes (Catuneanu et al., 1999), and linked to specific tectonic events in the adjacent orogen to the south. In contrast, Johnson et al. (1997) state that ?no significant unconformities are known to exist within the [Karoo] basin, with the possible exception of the one at the base of the Upper Triassic Molteno Formation?. The foreland basin model further suggests that foreland basin tectonics influenced Karoo stratigraphic relations right up to the base of the Drakensberg Lavas, which are inferred to represent continental rifting, prior to Late Jurassic-Early Cretaceous separation of east and west Gondwana. This paper presents an alternative model for stratigraphic evolution of the non-marine Upper Karoo Basin in which changes in stratal geometries, stacking patterns and accommodation space are explained in terms of thermally-induced pulsed crustal uplift and continental rifting prior to basalt eruption and the separation of east and west Gondwana.

Karoo Basin stratigraphy

The Karoo Basin fill (Karoo Supergroup) attains a maximum cumulative thickness of some 12000 m and ranges from Late Carboniferous to early Jurassic in age (Johnson et al., 1997). The Palaeozoic part of the succession consists of glaciogenic deposits suceeded by mudrock-dominated marine and brackish to fresh water sediments deposited contemporaneously with sand-dominated fluvio-deltaic systems which prograded into the basin from the northeast and south. The non-marine Mesozoic succession is confined to the central part of the basin where it consists of the Katberg and Burgersdorp Formations, overlain by the Molteno, Elliot and Clarens Formations comprising fluvio-lacustrine deposits laid down under conditions of increasing aridification, culminating in the onset of desert conditions and deposition of the predominantly aeolian Clarens Formation. The latter three formations are informally named the Stormberg group (Mid Triassic-Mid Jurassic) which forms a southeast thickening clastic wedge capped by some 1400 m of basaltic lava of the Drakensberg Volcanic Group (Mid Jurassic). The Molteno Formation at the base of the Stormberg group is unusual in that it comprises three northerly thinning clastic wedges (members) composed of a number of vertically stacked coal-bearing cycles enclosed within a sequence of arid to semi-arid fluvio-lacustrine red beds capped by aeolian sandstones. Most of the strata dip basinwards at low angles exposing successively higher stratigraphical units towards the centre of the basin in Lesotho.

Sequence stratigraphy of the Upper Karoo succession

The Upper Karoo succession may contain as many as four unconformities related to dated orogenic pulses (Catuneanu et al., 1999). The presence of these unconformities is not supported by field evidence which suggests a diachronous interfingering relationship (Cole, 1992). Thus, the significance, position and age of these unconformities, if indeed some of them exist at all, is poorly constrained. However, the degree of exposure, lateral continuity of outcrop and statistically-proven evidence of sediment cyclicity (Turner, 1975) in the Upper Karoo succession makes it ideal for sequence stratigraphic analysis and the location of significant unconformities (sequence boundaries) in the succession, by looking at changes in accommodation space.

Fischer plots

Fischer plots may be used to identify facies stacking patterns in any succession, including non-marine successions like the Upper Karoo, where stratigraphic systems and sediment cyclicity respond to changes in accommodation space. A preliminary accommodation plot has been compiled for the lower part of the non-marine Upper Karoo succession. This plot represents the first attempt to apply such techniques to the exclusively non-marine clastic Upper Karoo succession. Although only 13 cycles are depicted on the plot, individual cycles are thick and show a symmetrical trend making interpretation easier, and providing a basis for further work and in-depth analysis of sediment cyclicity. The plot shows a decrease in accommodation space followed by an increase in accommodation space in passing from low sinuosity channel facies to braided channel facies and back into low sinuosity/meandering channel facies moving up the succession. The only major change in accommodation space and stacking patterns, consistent with the presence of a significant sequence boundary (SB) unconformity, occurs at the base of the Indwe Sandstone Member, which defines the base of the Molteno Formation throughout the greater part the Upper Karoo basin, except in the south. This is consistent with a basinward shift in facies tracts and is succeeded by the climbing limb on the plot, which in traditional sequence stratigraphic terms corresponds to a transgressive systems tract (TST). The major sequence boundary identified by the plot has been previously attributed to source area uplift and erosion in response to lowered base level, consistent with an allocyclic forcing mechanism and abrupt change in accommodation space. This SB also coincides with a sudden shift from a predominant southerly source area below to a newly emergent, dominant southeasterly source area above.

Stratal geometries and stacking patterns

Stacking patterns compiled for the Molteno Formation show a general progradation trend for the lower part of the formation, when sedimentation rates exceeded the rate of accommodation space creation, with each successive sequence pushing progressively further northwards into the basin from a source area to the south. The overlying Indwe Sandstone Member shows a similar but much more extensive progradation trend consistent with its position above a low stand sequence boundary unconformity. The upper part of the succession (above the Indwe Sandstone) shows a progressive backstepping or retrogradational stacking pattern, consistent with a transgressive systems tracts (TST) or its alluvial equivalent, when sedimentation rates were less than the amount of accommodation space creation. These stacking patterns are identical to those predicted by the Fischer accommodation plot and clearly support the use of such plots for depicting cyclicity in entirely non-marine clastic successions.

The climbing limb on the accommodation plot, above the sequence boundary, extends into the lower part of the overlying succession (Elliot Formation) and is analogous to a transgressive systems tract (TST). However, in common with other fluvially-dominated systems the change from the TST to the alluvial equivalent of the overlying high stand systems tract (HST) is often difficult to recognise. This arises because HST's are characterised by a dominance of suspended load floodplain deposits and often resemble the TST, making it difficult to separate them in the absence of anything resembling a traditional maximum flooding surface. However, palaeovertisols/aridisols are abundant in this part of the Karoo succession, where there is a change from predominantly vertisols to aridisols moving upwards through the succession. Amalgamated, coarse-grained, braided sheet sandstones stack up above the sequence boundary. They show a high net to gross ratio and good connectivity indicative of a low rate of base level rise. The sandbodies become increasingly more isolated upwards passing into thinner, more isolated finer grained meandering channel sandbodies enclosed within floodplain fines of the alluvial equivalents of the TST and HST's. The boundary between these two systems tracts has been drawn where the change occurs from predominantly vertisols to aridisols, whose abundance in this part of the succession is consistent with limited accommodation space with a trend towards negative values in the equivalent of the upper HST.

The Molteno coal-bearing cycles are interpreted as 4th order prograding and regressive cycles which punctuate part of an overall 3rd order alluvial systems tract. If base level rise controls coal seam thickness then the thickest coals should occur at or near the transgressive maximum (Flint et al., 1995). This is not the case in the Molteno where the coal seams become thinner not thicker towards the top of the succession even though accommodation space (3rd order rise) is increasing. This anomaly probably reflects the increasing aridity of the climate in moving up through the succession from the Molteno to the overlying Elliot Formation. Many studies of the controls on stratal geometries have emphasized tectonics and eustasy, but have assumed a relatively constant climate which is not the case here where changing climate and tectonics are the major controls on base level change.

Interpretation of Upper Karoo stratigraphy

Volcanic material in the Upper Karoo succession suggest that volcanic activity began in the Anisian (~238 Ma). The volcanic material is mostly proximal and mafic in composition, it is chemically similar to the overlying Drakensberg Volcanics and is more abundant in the southeast. The chemical similarity between the volcanic material in the sediments and the Drakensberg Lavas suggests a chemogenetic link between them, and by implication, early volcanism and incipient rifting between east and west Gondwana. Evidence of early Gondwana rifting, unrelated to foreland basin tectonics, is provided by well-preserved Permo-Triassic rift sequences in East Antarctica, extensional features of Permo-Triassic age in Namibia and the Permo-Triassic coastal grabens in India.

Mantle plume model

Although the low stand sequence boundary unconformity and overlying low stand deposits represent a response to erosion and crustal uplift, no plausible mechanisms for this uplift have been proposed. The chemical similarity between some of the volcanic material in the Upper Karoo sediments and the Drakensberg Lavas, and the association of this uplift with volcanic outfall material suggests that it may have occurred in response to a thermal anomaly or hot spot which may have been linked to a deep seated rising mantle plume such as the Karoo plume. Such plumes provide a causal mechanism for sequence boundary unconformities. Mantle plumes are modelled as pulsed uplifts in which initial uplift and elevation of the crust is followed by a phase of more significant localised uplift and crustal updoming prior to broader scale maximum uplift preceding basalt eruption. Significant uplift is synchronous with crustal thinning and widespread, small-scale rifting, prior to continental separation, and it may result in aerially extensive minor volcanism several million years before separation. Significant localised updoming of 500-1000 m, or more, if it occurs directly above the anomaly, may occur 20-40 Ma before regional scale maximum uplift and basalt eruption. Such uplift may cause a significant fall in base level, and is capable of inducing crustal stresses initiating continental extension and rifting. The increased abundance of volcanic material in the southeastern part of the basin and decrease in thickness of the Drakensberg volcanic pile to the west suggests a volcanic source (thermal anomaly), some 150-200 km off the present southeast coast of South Africa within the offshore limit for Karoo volcanism (Griffiths and Campbell, 1990).

Stratigraphic response tp updoming

The lowermost (Bamboesberg) member of the Molteno Formation is confined to the southern part of the basin. Palaeocurrent and facies analysis shows that the main sediment source are at this time was located to the south in the Cape Fold Belt; the effects of the thermal anomaly in the southeast had relatively little influence at this time as the initial uplift, or rising solitons from the deeper seated plume, had only a minor effect on crustal updoming and changes in topographic relief. The rate of erosion was greater than uplift and sedimentation rates were greater than accommodation space producing progradational stacking patterns. In terms of the mantle plume model outlined above this initial uplift was followed by a hiatus and limited erosion prior to significant crustal uplift producing a major base level change and a basinwide low stand sequence boundary erosional unconformity. Rates of erosion remained high with sedimentation rates exceeding accommodation space producing a major basinwide pulse of sediment progradation. This erosional unconformity has been correlated with an important Mid-Triassic (~230 Ma) erosional event in east and west Gondwana (Veevers, 1989) but biostratigraphic controls are poor and no account has been taken of lag times. This low stand unconformity coincides with the switch from a southerly to a newly emergent, dominant southeast provenance located approximately 200 km offshore of the present coastline (Turner, 1975) of South Africa, in a similar position to that of the thermal anomaly. Above the main progradational phase the cycles show a regressive trend towards the southeast due to the effects of erosion on crustal updoming through time, when sedimentation rates were less than the available accommodation space. Significant crustal uplift due to the pulsatory thermal anomaly is interpreted to be equivalent to a 3rd order cycle punctuated by shorter 4th order cycles, possibly due to variable vertical flux or shorter episodes of subsidence superimposed on the overall upward trend due to crustal stretching.

The approximate position of this source area uplift lies just south of the Jurassic Karoo plume, but away from the direct influence of any known hotspots or hotspot tracks. Evidence for the existence of such a hotspot, such as vertical mantle heterogeneity, is difficult to prove in the Karoo volcanics because of the effects of contamination. At present there is no sedimentary evidence to suggest a northerly migration of the source area. Thus, the thermal anomaly may be related to the nearby Karoo plume or it may have been a transient, local thermal anomaly unrelated to the Karoo plume. Extension associated with the proposed thermal uplift is thought to be responsible for the minor, early volcanism that occurred during deposition of the Upper Karoo sediments. Tension induced by the rising plume leads to crustal stretching, which may then become the site of crustal thinning and later rifting. This may have occurred off the southeast coast of South Africa where crustal updoming and thinning were located close to the site of later rifting and separation of east and west Gondwana along the Agulhas Falkland Fracture Zone, which may also have been plume related (Ben-Avraham et al., 1997).

References

Ben-Avraham, Z., Hartnady, C.J.H. and Kitchin, K.A. 1997. Structure and tectonics of the Agulhas-Falkland Fracture zone. Tectonophysics, vol.282, 83-98.

Catuneanu, O., Hancox, P.J. and Rubidge, B.S. 1999. Reciprocal flexural behaviour and contrasting stratigraphies: a new basin development model for the Karoo retro-arc foreland basin, South Africa. Basin Research, vol.10, 417-439.

Cole, D.I. 1992. Evolution and development of the Karoo Basin. In: de Wit, M.J. and Ransome, I.G.D. (Eds.), Inversion Tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa. Balkema, Rotterdam, 87-100.

Flint, S.S., Aitken, J.F. and Hampson, G. 1995. The application of sequence stratigraphy to coal-bearing coastal plain successions: implications for the UK Coal Measures. In: Whatelely, M. and Spears, D.A. (Eds.), European Coal Geology. Geological Society London, Special Pubication, 82, 1-16.

Griffiths, R.W. and Campbell, I.H. 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth Planetary Science Letters, vol.99, 79-93.

Johnson, M.R., van Vuuren, C.J., Visser, J.N.J, Cole, D.I., de V. Wickens, H., Christie, A.D.M. and Roberts, D.L. 1997. The foreland Karoo Basin, South Africa. In: Selley, R.C. (Ed.), African Basins. Elsevier, Amsterdam, 269-317.

Turner, B.R. 1975. The stratigraphy and sedimentary history of the Molteno Formation in the main Karoo basin of South Africa and Lesotho. P.hD. Thesis (unpublished), University of the Witwatersrand, Johannesburg, 314p.

Veevers, J.J. 1989. Middle/Late Triassic (230±5Ma) singularity in the stratigraphic and magmatic history of the Pangean heat anomaly. Geology, vol.17, 784-787.

Biographical Notes

Brian Turner received his BSc Honours degree from the University of Hull in 1964. He worked in South Africa for the Geological Survey, before joining the University of the Witwatersrand, Johannesburg, where he was awarded M.Sc. (1969) and Ph.D. (1975) degrees in sedimentology. He returned to the UK in 1979 to take up a lectureship at the University of Newcastle upon Tyne before moving to his present position of Senior Lecturer in sedimentology in the University of Durham in 1989. His main research interests are in clastic depositional systems, particularly fluvial systems, fossil fuels and sedimentary ore deposits.