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Late Palaeozoic Basins of the Southern U.S. Continental Interior [Abstract] [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1982 **305**, 145-148
doi: 10.1098/rsta.1982.0030

Phil. Trans. R. Soc. Lond. A **305**, 145–148 (1982) [145]
Printed in Great Britain

Late Palaeozoic basins of the southern U.S. continental interior [abstract]

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The timing and geometry of late Palaeozoic inhomogenous deformation in the southern U.S. continental interior from the Appalachian foreland of Kentucky–Tennessee through Oklahoma and Texas to the Ancestral Rockies of Colorado–Wyoming–Utah can be definitively linked with a discrete sequence of collisional events in the Appalachian–Ouachita–Marathon orogenic belt to the south (Permian coordinates). A progressive staged collisional sequence beginning in late Mississippian times in the southern Appalachians and culminating in early Permian times in the Marathons led to a progressive deformation of the adjacent craton in a wide swath dominated by right-lateral shear (e.g. Rough Creek Fault zone) by which a Mexican promontory of North America was displaced towards a Pacific 'free face'. While the deformation in the Appalachian–Marathon belt was dominated by vertical plane strain leading to crustal thickening, the associated continental interior deformation can be averaged as a horizontal plane strain at or near sea level with localized deep extensional (Delaware) and flexural (Arkoma) basins and compressional uplifts (Amarillo–Wichita) giving local source areas.

Several distinct basin types can be recognized on the basis of position, geometry and subsidence history.

1. *Foreland basins immediately adjacent to the Appalachian–Marathon orogenic belt.* These, such as the Appalachian, Black Warrior and Arkoma Basins are asymmetric with cratonward onlap, clearly have a flexural origin with peripheral linear bulges (Cincinatti Arch, Llano Uplift), and resulted from the migrating thrust load of adjacent orogens. These basins show gradually increasing, then gradually decreasing, subsidence rates.

2. *Localized deep extensional basins linking offstepping strike-slip faults.* These basins (e.g. Magdalene Basin in the Canadian Maritimes and the Delaware Basin) are bounded by both steep and listrict faults, have stratigraphic sequences up to 10 km thick, and sometimes show basin margin thrusting of 'flower-structure' type. Their subsidence history follows a two-phase pattern predicted by the McKenzie (1978) model with a very rapid initial phase (crustal stretching) followed by a phase of exponential decline (thermal subsidence). For basins of this type, values for β of between 1.6 and 2.0 are usual, but in the Canadian Maritimes these are as high as 6.0 (Magdalene Basin) suggesting extremely attenuated crust, with local stretching of *ca.* 6 km. That marginal faults of such basins are growth faults is indicated by the eastern margin of the Delaware Basin where over 3 km of Wolfcampian black shale decreases to zero across the bounding fault system. These extensional basins have a distinctive cross-sectional shape that may be termed the 'Steer's head' or 'Texas Longhorn' geometry resulting from a rapid initial phase of fault-controlled subsidence in a stretching lithosphere with local isostatic compensation entirely within the basin. This is followed by a thermal

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phase with a thickening and strengthening of the lithosphere inducing compensation over an ever-widening area with basin margin onlap to produce the 'horns'. The complete absence of late Palaeozoic volcanism in extensional basins from Oklahoma to Colorado suggests that McKenzie's (1978) crustal attenuation model is more appropriate than the Royden *et al.* (1980) multiple asthenosphere dyke model, at least for these basins.

3. *Complex intracratonic basins that appear to show neither a simple flexural or clear extensional origin.* The Anadarko basin, for example, is asymmetric, bounded by a steep, possibly listric, thrust system to the south and a gradually thinning transition to the Kansas Shelf to the north. The likely origin of the Anadarko Basin is transpressional, that is the Amarillo–Wichita uplift overthrusts the southern margin of the basin with a component of left-lateral strike-slip. The localization of the Anadarko Basin seems to be due to the pre-existence of an early Palaeozoic rift, the South Oklahoma Aulacogen. The Val Verde Basin appears to be dominantly a flexural foreland basin adjacent to the Marathons but with a strong right-lateral component. The Paradox Basin, with its adjacent Uncompaghre Uplift, shows a bimodal subsidence history that suggests a stretching origin. Later thrusting on a flower structure above a right-lateral transform may explain the Pennsylvanian clastic flood from the Uncompaghre Uplift.

Hydrocarbon maturation calculations for the Delaware and Anadarko Basins indicate early maturation and long-distance migration. Most of the Midland Basin oil and gas probably originated 200 km away in the Delaware Basin and the Hugoton Field gas migrated some 300 km from the deep Anadarko Basin.

The McKenzie (1978) stretching model has a number of fundamental implications for the evolution of sedimentary basins, their deformation and their crustal structure, as follows.

(i) All transitions exist from $\beta = 1$ (no stretching) to $\beta = \infty$ (continental crust attenuated to zero) giving total conformable sediment thicknesses ranging from zero to 16 km and crustal thicknesses from 35 to 10 km (where basins are filled to sea level). Such transitions are seen both in intracratonic and rifted continental margin basins.

(ii) Consequently, all transitions exist from slightly stretched, through severely attenuated continental crust (with disorganized separation by ultramafic–gabbroic diapiric intrusion) and eventual virtual exposure of subcontinental mantle where $\beta \rightarrow \infty$ (para-oceans) to organized plate accretion and the growth of new, rather than the stretching of existing, surface area.

(iii) Because the post-stretching thermal re-equilibration of the lithosphere and the restoration of pre-stretching lithosphere thickness has a time constant of over 150 Na, the stretched lithosphere forms a zone of structural weakness for long periods that nucleates inversion zones or zones of subsequent compressional deformation. Obviously, the sooner after stretching that compression occurs, the easier it will be to invert a sedimentary basin because the lithosphere is still thin. As a basin ages and the lithosphere thickens, it becomes progressively more difficult to deform the sub-basin lithosphere. An analogous situation appears to be the obduction of oceanic lithosphere. Most obducted ophiolite nappes are emplaced as thin (10 km) flakes with hot subjacent aureoles less than 30 Ma after their generation by plate accretion, suggesting the increasing difficulty of detachment in older, thicker, colder lithosphere. The Laramide basement deformation of Colorado and Wyoming coincides remarkably with the Ancestral Rockies deformation, which latter deformation during the Pennsylvanian may have preconditioned the lithosphere for late Cretaceous – early Tertiary deformations.

(iv) Stretching of the continental crust yields sections in which mantle, high-grade metamorphic lower crustal rocks and low-grade upper crustal rocks and supracrustal stratigraphic sequences become more closely vertically spaced, hence enabling subsequent thrust flaking to emplace thin nappe sheets containing granulitic and mantle rocks over low grade sequences, a common relation in many orogenic belts.

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Discussion

A. S. MacKenzie. Do the authors have any direct measurements of present-day levels of organic metamorphism and if so, how do they fit their predicted values? Does the geometry of the traps require the organic matter to be oil or gas prone by the end of the Permian?

J. F. Dewey. All the ideas that I talked about have come from following the logical consequences of the stretching model. We have not examined whether measurements of maturation within these basins agree in detail with the model. The nature of the traps does not require the oil and gas to migrate earlier than the Permian. We have examined the maturity obtained from vitrinite reflectance of the Middle and Upper Permian rocks where we did not believe the maturity was sufficient to produce the hydrocarbons found nearby, and we found that the maturity was indeed insufficient to generate the oil and gas, which must therefore have migrated, in some cases over considerable distances.

M. F. Ridd. When calculating the maturation of these rocks did the authors take into account the effect on the maturation of the Permo–Carboniferous rocks of perhaps 3 km of Cretaceous and Tertiary rocks that are found on the flanks rather than the crest of the Hugoton Field?

J. F. Dewey. Much of the oil and gas in the Hugoton gas field could have come from Palaeozoic sediments in the Denver basin, which is a foreland basin. The section of Cretaceous and younger sediments above the Hugoton field is not sufficient to account for the observed level of maturation, though we did take them into account. The thick Cretaceous and younger section lies further to the west.

A. W. Bally. There is a great variety of source rocks, both lipid and humic, in west Texas and Oklahoma. For example, Pennsylvanian source rocks tend to be humic, but some of the Permian source rocks in the Delaware Basin are lipid. These source beds require different timespans to mature for oil and also for gas generation. Hood *et al.* (*Bull. Am. Ass. Petrol. Geol.* **59**, 986 (1975)) used a hole in the Anadarko Basin to calibrate their maturation scale, where there is no evidence for an upper Palaeozoic thermal event. In the Arkoma Basin, however, there appears to be a late Palaeozoic thermal event that is discordantly superposed on folded beds.

Before a stretching model is applied to the great variety of basins discussed in this paper, we should need a considerable amount of published information about their deep structure. Such information is generally difficult to obtain, and many of the seismic reflexion data are

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not very good. In the Anadarko Basin there appear to be some minor normal faults, on the north side, but if I remember correctly, these are synthetic faults, not antithetic (rotational) faults. Similar normal faults occur in the Arkoma Basin, and in the St Lawrence Lowlands of Quebec. These normal faults are formed during the same time brackets as the folding in the adjacent folded belts. I doubt that in the basins mentioned there is good evidence for an extensional event. The principal reason why the stretching model is unlikely to apply to this area is that the deformation that is most clearly observable was produced by compression. This is particularly well displayed in the Ardmore Basin, where there are many tight folds. Indications of reverse faults also occur on the Central Basin Platform. Thus there is hardly any evidence of late Palaeozoic rifting in west Texas and Oklahoma, and until such evidence is published, I am doubtful whether the stretching model can be applied there.

J. F. Dewey. I agree that the Arkoma and Ardmore basins were not produced by extension. The Arkoma basin is a foreland basin, with evidence of crustal thickening. The Ardmore basin is more complicated, and fits neither the loading nor the stretching model.

The faulting in the Delaware and Valverde basins of west Texas is not listric, since there is no evidence of rotation. The dip on the faults may even increase with depth.

D. H. Matthews, F.R.S. Present-day thermal gradients in the North Sea are thought to be profoundly affected by water flowing in aquifers. Might this effect disrupt the modelling of the maturation history of the sediments?

D. L. Turcotte. The first interpretation of the Cocorp line across the Anadarko basin suggests that it was produced entirely by compression.

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