Paleotectonic control of reservoir facies

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Abstract. The basement structural fabric of the Paradox basin affected sedimentary facies throughout Phanerozoic time. Continental-scale basement wrench-fault zones were rejuvenated repeatedly throughout the Paleozoic. The Paradox pull-apart evaporite basin was formed along the northwest-southeast-trending Colorado Lineament by basement faults of the northeast-southwest-trending Colorado Lineament. Structurally controlled shoaling conditions, formed by reaction of basement faults, fostered marine sandstone-reservoirs in Late Pennsylvanian time, crinoidal buildups in the Early Mississippian, and phylloid-algae mounds in Middle Pennsylvanian time. Apparently similar basement wrench-fault zones are present in Kansas. The midcontinent rift system is a northeast-southwest-trending fault zone that was rejuvenated during the Paleocene. Northwest-southeast-trending faults along the Central Kansas-Bourbon arch complex appear to have offset structures of the midcontinent rift. Both trends are interpreted to be continental-scale conjugate wrench-fault zones with rotational displacement along the midcontinent rift and denormal displacement along the Central Kansas-Bourbon arch complex. Stratigraphic relationships suggest repeated rejuvenation before Pennsylvanian uplift and erosion along the major structures. In both regions larger structural lineaments are associated with smaller-scale fault patterns. Reaction of these structures during time created paleostructural trapping conditions at several stratigraphic intervals. Evidence is accumulating in Kansas that tectonically controlled paleostructure and paleobathymetry are major predictable factors in reservoir localization. Recognition of reactivated basement structural fabrics can provide significant constraints on reservoir characterization and modeling.

Many stratigraphers base regional studies on the premise that sea-level fluctuations and their accompanying changes in tectonics and facies are the dominant influences on sedimentation, especially in Pennsylvanian and Lower Permian rocks. Recent studies by Vail (1987) and others emphasize the role of relative changes of sea level on sedimentation and the development of global unconformities. Sloan (1988, p. 1,665) insisted that "students and practitioners of sequence stratigraphy are, for better or worse, recorders and interpreters of tectonic evolution." There is no question that eustatic changes in sea level have significantly controlled sedimentation of late Paleozoic rocks, as with Pleistocene deposits, but tectonic controls continue to be important in facies modeling. What are the effects of structural deformation on sedimentation, and what is the extent of the tectonic activity to be expected? The answers depend on the geographic proximity to structurally controlled basins and uplifts and the local heterogeneities of the basement on which the sediments were deposited. Basins of deposition and upland sources of clastic sediments depend on structural control. Carbonate-sediments deposited on the shelves are hypersensitive to local water depth variations and to temperature, oxygen contents, etc., which in turn depend on the configuration of the seafloor. We must not only recognize the regional effects of structure, such as the locations of basins and uplifts, but also consider the effects of local variations of structurally controlled paleobathymetry when generating facies models. In addition, we may consider that the effects of tectonic activity are often cumulative and repetitive through geologic time. Nonuniform tectonic activity will invoke a complex history in the sedimentary record. Basement heterogeneity provides the template for specific sites where deformation is episodic and focused. Reactions of major basement structures have controlled the development of significant salt deposits in the Paradox basin in the southern Rocky Mountains region, and prolific petroleum production has been localized in paleocontinentally controlled carbonate reservoirs on the basin shelves. Eustatic sea-level changes were significant, but paleocontinentally controlled local reservoir development (Baars and Stevenson, 1982). The accommodation space for marine sedimentation is provided by a combination of sea-level fluctuation and structural deformation. Many stratigraphic and structural similarities that behave a comparative examination exist in the midcontinent.

Paradox basin

Baars (1966) and Baars and Stevenson (1982) demonstrated that the basement structural fabric of the Paradox basin (Utah and Colorado) affected sedimentary facies throughout Paleozoic time. Reaction of basement faults formed localized shoaling conditions conducive to shallow-water sedimentation. Continental-scale conjugate basement wrench-fault zones, originally activated 1.7-1.6 Ga, were rejuvenated repeatedly in Late Cambrian, Late Devonian, Early Missis-
sippian, Middle Pennsylvania, and Early Permian times (Baars, 1966). A northwest-southeast-trending swarm of basement faults, termed the Paradox-Wichita lineament, displays evidence of right-lateral displacement and provides the locus of basin subsidence (fig. 1) (Baars, 1974). A northwest-southwest-trending basement fault complex, termed the Colorado lineament (Warner, 1978), intersects the Wichita lineament in the basin, segmenting the Paradox into numerous subsalts (fig. 2). The Paradox well-apart salt basin was formed along the Paradox-Wichita lineament in Middle Pennsylvania time, facilitated by left-lateral faults of the Colorado lineament (Stevenson and Baars, 1986). These continental-scale basement lineaments conform to a global regmatic structural fabric that has been well documented in Precambrian and younger rocks (Salop, 1983; Hoppin and Pan, 1981).

Structurally controlled shoaling conditions in the Paradox basin, formed by reactivation of the basement structural fabric, were conducive to sites of localized shallow-water sedimentation. Strong northwesterly trends of reservoir facies invariably overlie present-day structurally high blocks. Thus reactivated high fault blocks fostered marine offshore bars in Late Devonian time, and these became effective sandstone petroleum reservoirs (Baars, 1966). Further reactivation of the basement blocks led to production of local crinoidal buildups in Early Mississippian carbonate rocks, forming excellent petroleum traps (Baars, 1966). Later growth along basement faults formed salter paleobathymetric shoals in Middle Pennsylvania time. The shoals hosted phylloid-algae mounds along the southwestern shelf of the Paradox salt basin (fig. 2); prolific oil producers, such as the Aneath and Bug fields, resulted (fig. 2) (Baars and Stevenson, 1983). The well-documented examples of structural influence on reservoir facies in the Paradox basin may serve as a working model for other regions where reactivation of basement structure is likely.

Midcontinent basement structure

Basement structural lineaments of the southern midcontinent, for example, the south-central Oklahomaaulicogen formed along the Paradox-Wichita lineament, have many similarities to those described in the southern Rocky Mountains. Earliest rifting and riftogenic igneous intrusions along this segment are dated at 550–525 Ma (Gilbert and McConnell, 1989). The Late Cambrian-Ordovician incipient Anadarko, Ardmore, and Marietta basins developed along the southern Oklahoma, aulacogen where up to 10,000 ft (3,000 m) of Cambrian-Ordovician sediments accumulated (Johnson, 1989). This deep structural trough lies in an analogous tectonic setting to the Paradox basin (fig. 1). The timing of the Oklahoma events coincides approximately with documented reactivation of the lineament in southwestern Colorado during Late Cambrian (Ignacian Quartzite) sedimentation (Baars, 1966) and the emplacement of northwest-trending tholeiitic diabase dikes along the adjacent Uncompahgre uplift (500 Ma) (Larson et al., 1985). Major Pennsylvania reactivations along the lineament were only slightly older in the Oklahoma basins than in the Paradox basin (Johnson, 1989), resulting in
similar tectonic histories. The northern shelf of the Anadarko basin, like the southwestern shelf of the Paradox basin, was paleotectonically controlled; both underwent significant subsidence during the Pennsylvanian and the Permian. In both cases the reactivated basement structure localized reservoir facies and unconformity relationships on the structurally high basin margins.

**Kansas basement structure**

Paleozoic strata were deposited in Kansas on broad platforms, ramps, shallow basins, and localized uplifts. The location of these structural features varied throughout the Paleozoic, but consistent patterns of repeated localized uplift and subsidence are noted. From the midcontinent rift systems in the Precambrian to the north Kansas basin and Oklahoma basin in the early Paleozoic and the Anadarko, Arkoma, Salina, Forest City, and Sedgwick basins in the late Paleozoic, a clear pattern of deformation geometries emerges. Structures apparently similar to basement wrench-fault zones of the Paradox basin underlie the 6-7 Cenozoic section (fig. 3).

The midcontinent rift system and basinally related Hunsbädt fault zone, dated at 1.1 Ga, constitute a north-northeast-south-southwest-trending fault swarm, the general location of which corresponds to the rifted zone, was reactivated several times during the Paleozoic. Northwest-southeast-trending faults along the Central Kansas-Bourbon arch complex appear to have offset structures of the midcontinent rift (fig. 4), although elements of the rift continue southward into the Sedgwick basin and the structural zone appears to broaden by splaying. Both trends are interpreted to be continental-scale conjugate wrench-fault zones with sinistral displacement along the midcontinent rift (Berendsen and Blair, 1986) and dextral displacement along the Central Kansas-Bourbon arch complex (Baars, 1990) (fig. 4). Faulting observed on the Kansas escarpment (deep reflection seismic) line and northeast-southwest-trending lineaments observed on gravity and magnetic maps across the midcontinent rift system coincide with faults and anticlines observed in the much younger Paleozoic strata. Also, trends of kimberlite deposits in Kansas follow basement discontinuities (Watney, 1983; Berendsen and Blair, 1986; Newell et al., 1987; Berendson et al., 1988).

Stratigraphic relationships suggest a long history of reactivation. The structurally controlled Precambrian hills to the Central Kansas uplift (Waters, 1946, 1958) were first buried by the Cambrian-Ordovician Arbuckle Group, which was locally removed by pre-Simpson erosion on structurally
elevated fault blocks. The Middle Ordovician Simpson Group overlaps the Arteskls and rests directly on Precambrian basement at several localities along the northern midcontinent rift and Nemaha complex and locally on the Central Kansas uplift (Walters, 1958). Local uplift and interstratal truncation suggest reactivation of structural blocks during the Late Ordovician, before the better known Pennsylvanian uplift and erosion of the major structural features (Dolton and Finn, 1980).

As in the Paradox basin, major structural lineaments in Kansas are associated with smaller-scale rhomboidal fracture patterns, drag-related en echelon folds, and complex, mutually offsetting fault patterns, especially in areas of intersecting basement structures. Reactivation of these structural features throughout time created unconformity-bounded trapping conditions at various stratigraphic intervals.

A typical example of episodic structural reactivation was documented in western Russell County, central Kansas, by Walters (1978, p. 60):

The...Corbin Oilfield is localized by a broad gentle anticline overlying a faulted Precambrian basement high. There is a displacement of 300 feet in the Precambrian granite. Faulting accounts for 50 feet of relief on the sub-Pennsylvanian unconformity surface...At the level of the oil producing Lansing-Kansas City limestone...faulting is observed to the extent of 50 feet of the total relief of 100 feet. The Parkhaven Salt has a thickness of less than 250 feet overlying the structural high, as compared with over 300 feet in the surrounding synclinal areas. The Permian Stone Coral Anhydrite at the top of the Sunflower Group...shows 30 feet of steep dip overlying the fault zone. Careful surface mapping of the outcropping Cretaceous Fence Post Limestone in the early 1920s disclosed 30 feet of a closure, leading to the discovery of the oilfield in 1925.

In numerous examples, structurally controlled paleo-bathymetry localized phylloid-algae banks and lime-sand accumulations in Pennsylvanian carbonate rocks. For example, Cahoj field, located on the upper shelf of the Anadarko basin, shows structural control on facies development. Other fields in the adjoining area of Hitchcock County, Nebraska, also exhibit structural control (Walters, 1980, Dubois, 1985).

The Lansing and Kansas City groups are composed of a series of carbonate-dominated cycles deposited over extensive areas of a broad shelf in Kansas. Detailed mapping of the thickness and facies of the components of these cycles indicates clear correlations with contemporaneous local shelf topography related in many instances to sites of basement uplift. Multiple episodes of uplift can be attributed to these structures, including structural deformation during the cyclical events and during both earlier and later periods. For example, in Cahoj field Pennsylvanian strata rest directly on the Cambrian-Ordovician Arbuckle Group, whereas in the...
surrounding area the Pennsylvanian overlies Mississippian limestones. Thicker shallow-water carbonate deposits and po-
nosity development occur both on and flanking Cahoy field (figs. 5 and 6). Nonmarine shales, which overlie the carbon-
ate reservoirs and cap each cycle, thin to 80% over these
fields (fig. 7). These shales are assumed to have been pas-

dively deposited and are thicker in topographic lows. Local
shading of this shale provides a means to detect topographi-
cally positive sites.

Early subaerial diagenesis and weathering and erosion
occurring at the close of each of the cycles in the Lensing and
Kansas City groups are also closely linked to local
paleotopography. Dubois (1985) notes deeper and more
extensive solution cavity development (microkarst) on the
flanks of the structures, probably reflecting a greater amount
of available undersaturated ground water in these lower
areas. The highs are affected by more subtle dissolution

events.

In contrast to the upper shelf, the lower shelf setting
around the Anadarko basin in southwestern Kansas was a
broad ramp developed during most cycles. Extensive tracts
of oolitic grainstones accumulated on this ramp. Local struc-
tures, such as those at Victory field (Watney and French,
1986) and Collifer Flats field (Watney, 1985), are associated
with unusually thick oolitic grainstones (figs. 8 and 9).
In addition, other cycles in Victory field have grainstone depos-
its that flank the more positive areas of the field. Positive
areas may or may not be sites for grainstone sedimentation,
depending on the duration of sea-level stands during
shallowing conditions across the ramp. Episodic structural
movement, involving that which occurred during deposition,
and eustatic sea-level changes resulted in marked control on
reservoir development.

In general, western Kansas sedimentation was signif-

cantly modified by progressive, regional structural deforma-
tion that extended through the course of accumulation of the
Kansas City Group (Watney, 1985). This affected both the
type and location of depositional facies and the nature of
diagnostic overprinting. The deformational pattern is linked to
basement heterogeneity and tectonism.

A study in progress at the Kansas Geological Survey
has revealed a high basement fault block in east-central Mont-
gomery County in southeastern Kansas. According to sub-
surface data an apparently northwest-dipping fault running
approximately through the town of Independence has a
vertical displacement of more than 1,000 ft (300 m) at the top
of the Permian basement. Northeasternly conjugate faults
form an orthogonal high block. Potential-field mapping con-

firms the presence and orientation of the structure and indi-
cates that a wedge of basaltic basement rock occurs on the
down side within a regional granite-rhyolite terrane. Cam-
brian-Ordovician Arbuckle beds thin from 863 ft (263 m) on
the down side to 416 ft (127 m) on the high side of the fault.
Surface and near-surface studies by Evan Franseen and
Howard Feldman (personal communication, 1990) indicate
the presence of a thickened deluge wedge in the Cherryvale
Shale coincident with the southwestern corner of the base-
ment fault block and a locally thickened oolite facies of the
Deum Limestone Member parallel to and coincident with the
major fault. This is clearly a case of facies localization in
Pennsylvanian strata controlled directly or indirectly by
recurrent basement structure.
On a larger scale in southeastern Kansas prominent episodes of sea-level rise and the formation of a carbonate platform extended through two cycles in the Kansas City Group (approximately 20 mi (30 km) southward migration during each period). These two intervals of progradation were succeeded by another cycle that reflects notable backstepping of the shelf margin of at least 35 mi (56 km) (Watney et al., 1989). Tectonism in the Arkoma basin (foreland basin) to the south may have been responsible for the backstepping of the shelf. An abrupt rise in eustatic sea level may also have been a cause of shelf retreat. Blocky, linear shelf margins suggest that basement heterogeneity may have been important in defining the character of the shelf margin. The combined effects of tectonic subsidence, eustatic sea-level changes, and sedimentation of these deposits through computer simulation have been addressed by French and Watney (1990) and Watney et al. (this volume).

The assessment of controls on sedimentation requires an understanding of the evolving local and regional shelf configuration (subsidence and uplift) coupled with sea-level history. It is impossible to interpret low accommodation for sedimentation evolved unless both are considered in a quantitative manner (rates of change, duration, and magnitude).

Myriad possibilities exist in Kansas for localized palaeotectonic maps associated with these structures. Detailed facies analysis, such as that published on the Viola Limestone by Bornmann et al. (1982), will undoubtedly disclose numerous examples of localized reservoir facies in other Palaeozoic stratigraphic intervals.
Figure 8. Carbonate facies map of upper regressive H zone carbonates in Rawlins County, Kansas. Cuttings and core control points are labeled. Facies include thick phylloid-algae mudbank and a grainstone shoal separated by areas of skeletal lime mudstone to wackestones. Divisions shown within packstone facies separate areas in which the types of skeletal particles are different. Grainstone shoals in the north overlie Caboy structure (compare with fig. 7). Carbonate mudbank is the south-central area is situated on a structural high, whereas mudbanks are located in modern structural lows (from Wamety 1980).
Figure 7. Thickness of nonmarine sediments of F zone in Hitchcock County, Nebraska. There is notable thinning of shale over producing areas (from Dobson [1985]).

Figure 8. Structure contour map on top of K zone. Well symbols denote production status in the zone. Shading indicates areas with elevations above -16.0 ft (-4.9 m) (from Wateney and French [1988]).
Conclusions

Evidence is accumulating in Kansas that tectonically controlled paleotopography and paleobathymetry are major prediction factors in reservoir localization. Recognition of reacted regressive basin structural fabrics is important to facies and reservoir analysis and can provide significant constraints on reservoir characterization and modeling.

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References


