Development of Crestal Collapse Structures above Dissolving Salt Anticlines: Application to Seismic Interpretation within Salt-Controlled Basins*

Tom Randles[1], Stuart Clarke[1], and Phil Richards[2]

Search and Discovery Article #41033 (2012)*
Posted October 8, 2012

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012, AAPG©2012

[1]Keele University, Keele, United Kingdom (t.a.randles@epsam.keele.ac.uk)
[2]British Geological Survey, Edinburgh, United Kingdom

Abstract

Salt-controlled basins represent some of the principal hydrocarbon provinces of the world. Their potential, and their exploitation, are governed by complex three-dimensional interactions between host sediments and structural geometries related to salt mobility. However, the limitations of seismic reflection data, particularly with respect to resolution, are such that much of the complexity of salt-controlled regimes is often overlooked. In the UK Central North Sea, structures related to the Tertiary dissolution and subsequent crestal collapse of salt walls provide ideal geometries for hydrocarbon entrapment, but are poorly imaged on seismic data. An in-depth understanding of the structural styles that control salt wall collapse, particularly at the 'sub-seismic' scale, is essential in order that meaningful interpretations of potential prospects can be made based on seismic data.

The excellent exposure and preservation of a number of collapsed salt walls and related structures within the Paradox Basin, southeast Utah, USA, provides an ideal opportunity to investigate the structural development of crestal collapse structures at field scale. Detailed structural mapping and satellite image interpretation provide input to a series of idealised three-dimensional numerical models that represent the key structural styles that facilitate crestal collapse of the salt wall. These summary models are used to improve upon previous interpretations of seismic data across equivalent structures from the UK Central North Sea.

Crestal collapse of salt walls in the northern Paradox Basin is shown to be controlled primarily through development of a single listric fault, with an associated hanging-wall rollover anticline. Hanging wall faults systems are highly complex, comprising numerous syn- and antithetic normal faults with an en-echelon arrangement, showing displacements typically in the range of 10-50 metres. Faults commonly show rapid changes in displacement along strike, resulting in complex accommodation zone geometries and numerous small closed structures. An improved interpretation of seismic data across collapsed salt walls from the UK Central North Sea is presented based on these summary models.

This work represents the early stages of development of one of the first detailed frameworks to guide interpretation of seismic data in salt-controlled basins, and has application to both exploration and production in sub-surface salt-controlled hydrocarbon provinces.

Introduction

It is well known that accommodation zones play an important role in the migration of hydrocarbons across faults which would otherwise act as barriers to fluid flow (e.g. Rotevatn et al. 2007), and with hydrocarbon prospects becoming ever more challenging, a deeper understanding of charge routes into reservoirs, and their trapping potential, is paramount to their successful exploitation. Whilst the fundamental mechanisms behind simple accommodation zones, (e.g. a single relay-ramp structure), are relatively well established (e.g. Peacock and Sanderson 1991, 1994), more complex examples involving numerous faults and interlinked relay ramp structures, their relationship to deformational styles, and their influence on fluid migration, remain poorly understood.

Of particular current interest to the hydrocarbons industry are those accommodation zones that occur within fault systems that are related to, or influenced by, salt movement. Active hydrocarbon provinces including the Gulf of Mexico, the UK Central North Sea, and the West African Salt Basin, are characterised by salt walls that provide ideal hydrocarbon trapping geometries both along their flanks, and within palaeo-topographical depressions often present at their crests (Wakefield et al. 1993; Stewert et al. 1999). In both cases, potential trapping geometries are the result of extensional deformation of the overburden related to dissolution of the salt wall crests and/or regional tectonic stresses. This deformation is controlled by a range of structural styles that change rapidly along the length of the salt wall over relatively short distances, with displacement transferred between these styles via complex accommodation zones that are likely to impose strong controls on potential charge routes.

Attempts to evaluate and risk any potential hydrocarbon traps and migration pathways associated with salt walls are severely hindered by the limitations of seismic reflection data – the principle sub-surface datasets employed by industry to investigate potential hydrocarbon accumulations. Within the accommodation zone, displacement is transferred via numerous small faults with offsets that are commonly less than the resolvable limits of the data. Where significant dissolution has taken place at the tops of salt walls, these small faults are almost indistinguishable from background noise.

Exceptional exposures of salt wall-related accommodation zones have been identified within key areas of the Paradox Basin, Utah, U.S.A. (Figure 1), where horst and graben structural styles along the crests of salt walls give way, over distances of less than one kilometre, to structural styles dominated by a single listric fault with an associated rollover anticline in the hanging-wall. These exposures offer a valuable opportunity to evaluate the three-dimensional geometry of the accommodation zone at field scale, providing an analogue for those features at the crests of salt walls that are so difficult to interpret in the sub-surface.

This work represents the early stages in the development of one of the first detailed frameworks with which to guide seismic interpretation within salt-controlled basins. Field data collected from the Paradox Basin provide the basis for a set of three-dimensional summary models for the structural styles that are present adjacent to, and within, salt wall-related accommodation zones. These models are applied to seismic data from some of the best-characterised subsurface analogues, including the UK North Sea, as a method for evaluating the application of field-scale modelling techniques to seismic data. A range of numerical techniques, including discrete element modelling and stochastic fluid flow simulations, are employed to investigate the structural development and kinematics of these structures, and to assess the effects that they may have on hydrocarbon migration pathways into potential trapping structures.

The Salt Anticlines of the Paradox Basin

The characteristic topography of the Salt Anticline Region of the Paradox Basin reflects the areas complex history of structural deformation and salt movement. During the middle Pennsylvanian to early Permian periods, the thick evaporitic strata of the Pennsylvanian Paradox Formation began to flow towards the southwest in response to differential loading by clastic wedges shed from the Uncompahgre Uplift, a structural high that forms the northeastern margin of the basin (Jones 1959; Doelling et al. 1995), resulting in the development of a number of salt walls that align with northwest-trending, pre-existing basement faults (Cater 1970; Doelling 2000). Subsurface data suggest that each salt wall grew by a process of ‘downbuilding’, with some salt present at the surface throughout salt wall development, and Permian sedimentation forming mini-basins on each flank (Lawton & Buck 2006; Trudgill 2009).

Consequently, sediments deposited throughout the Permian and Triassic periods, comprising the Cutler Group and Moenkopi Formation (Figure 2), were syn-diapiric, showing considerable thickness changes and or truncations across the crests of the salt walls

(Doelling et al. 1995). The main phase of diapirism ceased sometime during the Triassic Period as salt supplies were exhausted, and deposition of late Triassic through to Cretaceous age sediments, including the Chinle Formation, deposits of the Glen Canyon and San Rafael Groups, and Morrison Formation (Figure 2), were largely post-diapiric. The salt anticlines were accentuated as a result of west – southwest compression of the region during the late Cretaceous Laramide Orogeny, which also led to the development of synclines between each salt wall (Heyman et al. 1986; Doelling et al. 1995).

Large northwest-trending normal faults, including the Moab Fault and the Salt-Cache Valley Faults, exploit the mechanical weakness of the salt walls along their length, and are thought to have been active from the late Cretaceous through to Quaternary periods (Foxford et al. 1996). Generally accepted theories attribute these faults to dissolution of the Paradox Formation evaporites that form the cores of the anticlines following Tertiary uplift of the Colorado Plateau, resulting in the gravitational collapse of the overlying post-diapiric sediments (Baker 1933; Stokes, 1948; Cater 1970; Doelling 2000; Gutiérrez 2004). However, several lines of evidence suggest that regional tectonic extension may have contributed to collapse of the anticline crests, with deformation localised on the salt walls, and salt dissolution providing only minor or secondary controls on collapse geometries (Vendeville and Jackson 1992a,b, 1994; Ge and Jackson 1998).

A range of collapse mechanisms have been identified above the salt walls, ranging from ductile deformation of the overburden, creating sags, to brittle deformation creating graben and half-graben geometries (Figure 3). Collapse mechanisms have been linked to the radius of curvature of the salt anticlines, with long wavelength anticlines dominated by ductile deformation, and short wavelength anticlines dominated by brittle collapse (Cater 1970). Where collapse mechanisms are brittle in nature, horst-graben structural styles tend to change over very short distances into styles with half-graben geometries, particularly where salt walls terminate. The nature of the accommodation zones that facilitate the transfer of displacement between these styles, and the parameters that control the positions of these rapid changes in structural style, are poorly understood.

Results

Detailed structural mapping based on satellite image interpretation and field survey has been used to investigate the geometry, deformational characteristics and development of collapse structures from the Paradox Basin, Utah. Key areas along the flanks of the Paradox Basin salt anticlines, where small-scale collapse structures in post-diapiric strata are particularly well exposed, were targeted and used to develop summary models of individual structural styles present above the salt walls.

The flanks of collapse structures tend to be dominated by large-scale, en-echelon normal faults several kilometres in length that dip towards the core of the anticline, with deformation between these faults accommodated via numerous, small-scale faults with relatively low displacements with respect to their length; this is attributed to the apparent tendency of faults to develop via the propagation and hard-linking of several individual fault segments, a process that appears to be common within fault systems of all scales that are related to anticline collapse. As a result, strikes can vary significantly, and displacements are relatively low for any given fault length.

Within Salt Valley, Arches National Park, where collapse appears to be controlled by development of a crestal graben, the crest of the salt anticline is characterised by chaotic fault block geometries that are thought to be isolated from the anticline flanks and entrained within the exposed Paradox Formation that forms the floor of the valley. Despite the reduced width of the valley at the northern end of Salt Valley, current interpretations show a graben geometry, juxtaposing the Cretaceous Mancos Group within the valley against Triassic and Jurassic deposits on the anticline flanks (Gard 1976; Doelling 1985). However, the distribution of fault blocks farther to the south, where the valley is at its widest, implies that displacement was initially localised on a single fault running along the crest of the salt wall.

Where salt walls terminate, half-graben structural styles tend to dominate, demonstrating clear rollover anticlines within the hanging-wall. Field data from the end of the Moab-Spanish Valley salt structure, complimented with structural data from available borehole reports and published geological maps, has provided input to a three-dimensional structural model of the fault system present at the termination of the salt wall (Figure 4). The Moab Fault dips approximately 65° towards the northeast, and has a displacement of approximately 900 metres within the area modelled. Hanging-wall faults are predominantly synthetic, with displacements not exceeding 30 – 50 metres. A set of antithetic faults with displacements greater than 50 metres bound the rollover anticline, and step progressively back from the Moab Fault as they approach the salt wall (Figure 5). Initial results suggest that these antithetic faults comprise a key architectural element of the accommodation zone within which displacement is transferred between graben and half-graben structural styles.

Well-imaged subsurface analogues for the Paradox Basin salt walls have been interpreted using a high quality 3D seismic dataset from the UK Central North Sea. The dataset is characterised by several east – west and southeast – northwest trending salt walls belonging to the Permian Zechstein Group that show collapse structures at their crests related to regional extension. Both horst and graben and half-graben structural styles have been identified within the overburden at the salt wall crests, however in most instances, the bulk of displacement appears to be localised on a single normal fault that detaches in the salt. In several cases, the faults are oriented at an oblique angle to the trend of the salt walls. Hanging wall structures are best imaged where half-graben geometries exist with clearly defined hanging-wall rollover anticlines, and typically comprise en-echelon normal faults with displacements greater than 50 metres. Smaller faults, including those related to the accommodation zones between en-echelon fault strands, are present but are not resolvable as individual features from the data.

Discussion and Further Work

Early comparisons of field observations from the Paradox Basin with equivalent sub-surface examples from the UK Central North Sea suggest that deformation at the crests of salt walls may initiate along single, large-scale normal faults with associated rollover anticlines, rather than developing as true graben structures. Continued collapse of the overburden may result in the 'breach' of the rollover anticline via a series of en-echelon, antithetic normal faults in the hanging-wall. The resulting structure has displacement concentrated on a single normal fault, with brittle deformation of the hanging-wall and footwall generating a graben-like geometry. This may suggest that graben and half-graben geometries do not represent end-member structures in salt provinces, and may be linked through accommodation zones of recognisable geometry. This has potential implications for the accurate risking of hydrocarbon traps and migration pathways related to salt walls.

The application of summary models developed using field data from the Paradox Basin salt structures to seismic data from the UK North Sea is being tested to evaluate their potential as a tool to guide seismic interpretation. Based on these models, we can infer the presence and geometry of numerous sub-seismic scale faults that are likely to have developed via a process of segment linkage. Small-scale structures are likely to be synthetic in nature, and may have considerable implications for fluid migration pathways and reservoir compartmentalisation.

Further work will employ stochastic fluid flow modelling techniques to evaluate the effects of these sub-seismic scale structures on charge routes into potential trapping structures. Additionally, a range of techniques, including discrete element modelling and statistical methods, will be used to evaluate the kinematics and development of different structural styles, and to investigate the parameters and conditions that control their geometry and position within salt-controlled basins.

References

Baker, A.A., 1933, Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U.S. Geological Survey Bulletin 841, 95 p.

Cater, F., 1970, Geology of the salt anticline region in southwestern Colorado: U.S. Geological Survey Professional Paper 637, 80 p.

Doelling, H.H., 1985, Geologic map of Arches National Park and vicinity, Grand County, Utah: Geologic Map 74, Utah Geological Survey, 1 map.

Doelling, H.H., M.L. Ross, and W.E. Mulvey, 1995, Interim geological map of the Moab Quadrangle, Grand County, Utah: Utah Geological Survey, Open-file report 322, 100 p.

Doelling, H.H., 2000, Geology of Arches National Park, Grand County, Utah, in D.A. Sprinkel, T.C. Chidsey, and P.B. Anderson, (eds.), Geology of Utah's Parks and Monuments: Utah Geological Association Guidebook, v. 28, p. 11-36.

Doelling, H.H., 2001, Geologic map of the Moab and eastern San Rafael Desert 30' x 60' quadrangles, Grand and Emery Counties, Utah, and Mesa County, Colorado: Geologic Map 180, Utah Geological Survey.

Doelling, H.H, 2004, Geologic map of the La Sal 30' x 60' quadrangle, San Juan, Wayne and Garfield Counties, Utah, and Montrose and San Miguel Counties, Colorado: Geologic Map 205, Utah Geological Survey.

Foxford, F.A., I.R. Garden, C.S. Guscott, S.D. Burley, J.J.M. Lewis, J.J. Walsh, and J. Watterson, 1996, The field geology of the Moab Fault, *in* A.C. Huffman, Jr., W.R.
Lund, and L.H. Godwin, (eds.), Geology and resources of the Paradox basin: Utah Geological Association Guidebook, v. 25, p. 265-283.

Gard, L.M., 1976, Geology of the north end of the Salt Valley Anticline, Grand County, Utah: U.S. Geological Survey Open-file report 76-303, 35 p.

Ge, H., M.P.A. Jackson, 1998, Physical modelling of structures formed by salt withdrawal: Implications for deformation caused by salt dissolution: AAPG Bulletin, v. 82/2, p. 228-250.

Gutiérrez, F., 2004, Origin of the salt valleys in the Canyonlands section of the Colorado Plateau: Evaporite-dissolution collapse versus tectonic subsidence: Geomorphology, v. 57, p. 423-435.

Heyman, O.G., P.W. Huntoon, and M.A. White-Heyman, 1986, Laramide deformation of the Uncompahgre Plateau – geometry and mechanisms, *in* D.S. Stone, and K.S. Johnson, . (eds.), New interpretations of northwest Colorado geology: RMAG, p. 65-76.

Lawton, T.F., and B.J. Buck, 2006, Implications of diapir-derived detritus and gypsic paleosols in Lower Triassic strata near the Castle Valley salt wall, Paradox Basin, Utah: Geology, v. 34/10, p. 885-888.

Peacock, D.C.P., and D.J. Sanderson, 1991, Displacements, segment linkage and relay ramps in normal fault zones: Journal of Structural Geology, v. 13/6, p. 721-733.

Peacock, D.C.P., and D.J. Sanderson, 1994, Geometry and Development of Relay Ramps in Normal Fault Systems: AAPG Bulletin, v. 78/2, p. 147-165.

Rotevatn, A., H. Fossen, J. Hesthammer, T.E. Aas, and J.A. Howell, 2007, Are relay ramps conduits for fluid flow? Structural analysis of a relay ramp in Arches National Park, Utah, *in* L. Lonergan, R.J.H. Jolly, K. Rawnsley, and D.J. Sanderson, (eds.), Fractures Reservoirs: Geological Society of London, Special Publications, v. 270, p. 55-71.

Stewart, S.A., S.I. Fraser, J.A. Cartwright, J.A. Clark, and H.D. Johnson, 1999, Controls on Upper Jurassic sediment distribution in the Durward – Dauntless area, UK Blocks 21/11, 21/16, *in* A.J. Fleet, and S.A.R. Boldy, (eds.), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference: The Geological Society, London, p. 879-896.

Stokes, W.L., 1948, Geology of the Utah – Colorado salt dome region with emphasis on Gypsum Valley, Colorado: Utah Geological Society, Guidebook to the Geology of Utah, v. 3, p. 40-50.

Trudgill, B., 2009, Evolution of salt structures in the northern Paradox Basin: controls on evaporite deposition, salt wall growth and supra-salt stratigraphic architecture: Basin Research, v. 23/2, p. 208-238.

Jones, R.W., 1959, Origin of salt anticlines of Paradox Basin: AAPG Bulletin, v. 43/8, p. 1869-1895.

Vendeville, B.B., and M.P.A. Jackson, 1992a, The rise of diapirs during thin-skinned extension: Marine and Petroleum Geology, v. 9, p. 331-353.

Vendeville, B.B., and M.P.A. Jackson, 1992b, The fall of diapirs during thin-skinned extension: Marine and Petroleum Geology, v. 9, p. 354-371.

Vendeville, B.B., and M.P.A. Jackson, 1994, Regional extension as a geologic trigger for diapirism: GSA Bulletin, v. 106, p. 57-73.

Wakefield, L.L., H. Droste, M.R. Giles, and R. Janssen, 1993, Late Jurassic plays along the western margin of the Central Graben, *in* J.R. Parker, (ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference: The Geological Society, London, p. 459-468.

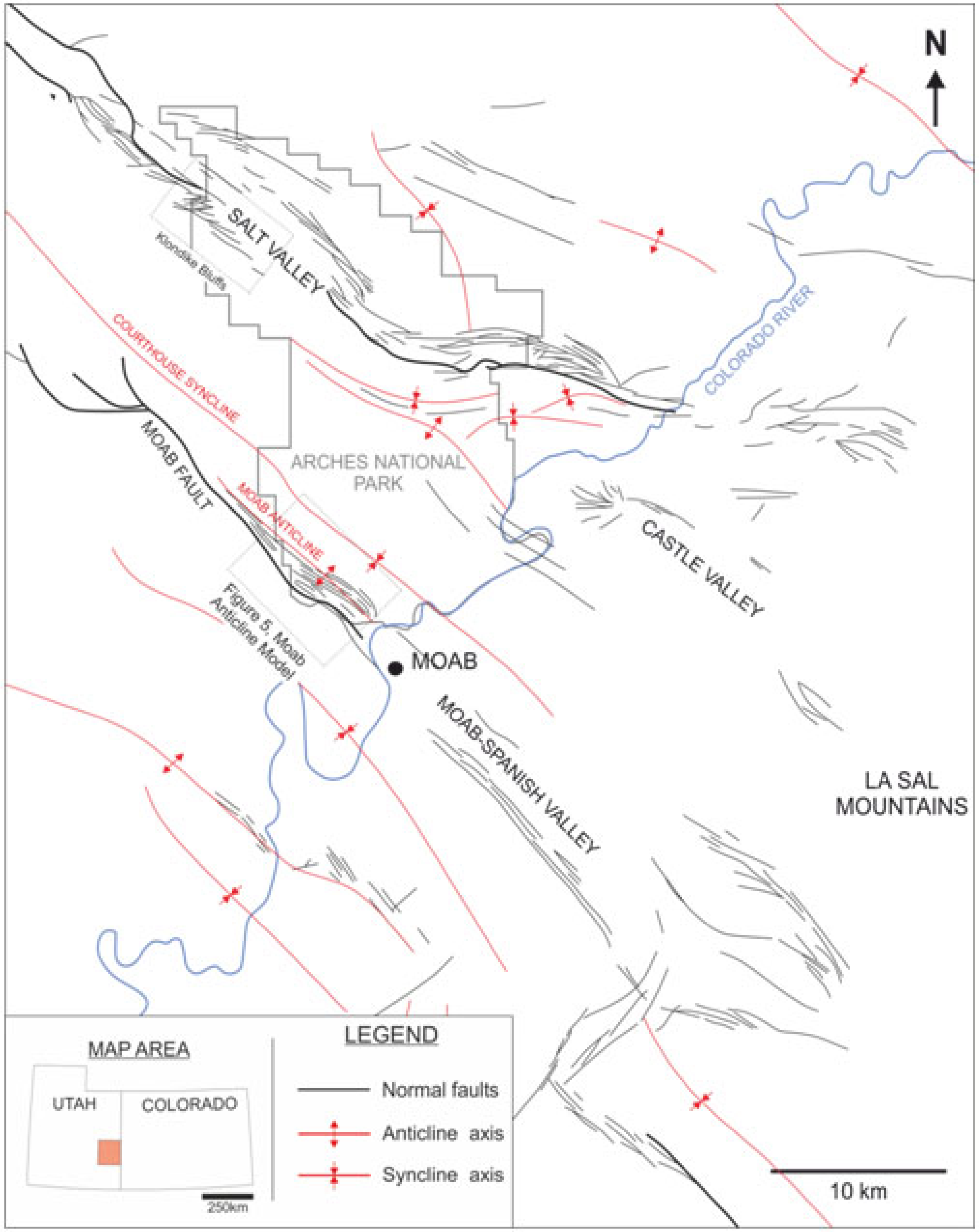

Figure 1. Structural map of the Salt Anticline Region of the Northern Paradox Basin, after Doelling (2001, 2004). Extensional faults are Tertiary in age, and are related to dissolution and collapse of the crests of several northwest-trending salt-cored anticlines. Gentle folding is related to Laramide compression and accentuates the salt anticlines.

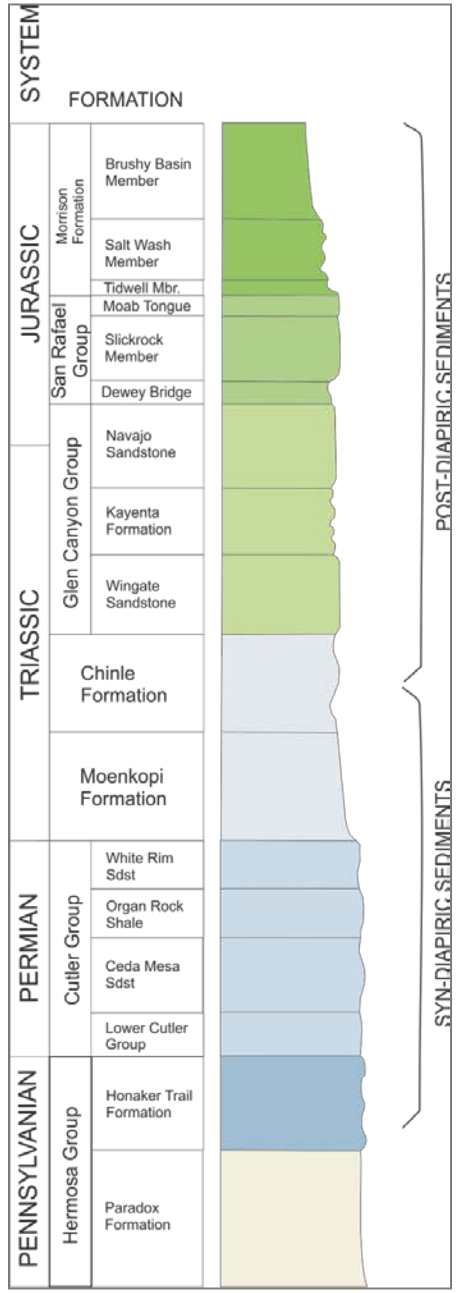

Figure 2. Stratigraphy of the Paradox Basin, after Doelling (1985). The overburden above the dissolving salt-cored anticlines consists of a thick succession of Jurassic and Cretaceous sandstone formations that were deposited after initial salt movement had ceased.

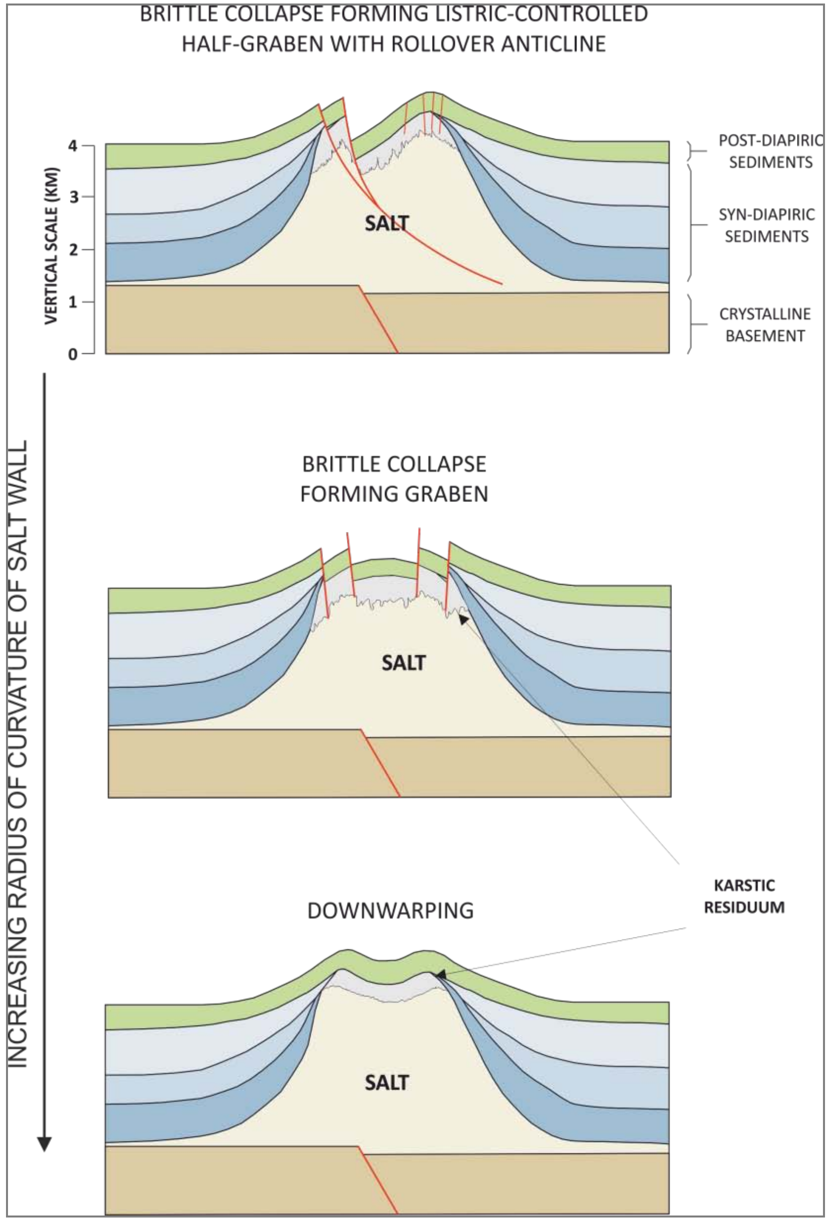

Figure 3. Crestal collapse geometries recognised above the Paradox Basin salt-cored anticlines, after Gutiérrez (2004). Salt valleys in the northern Paradox Basin are dominated by brittle collapse, with graben geometries developing where valleys are at their widest and half-graben geometries developing where salt walls terminate. Ductile downwarping is prevalent among the salt valleys of the southern Paradox Basin, Colorado, where valleys are typically two to three times the width of those in the north.

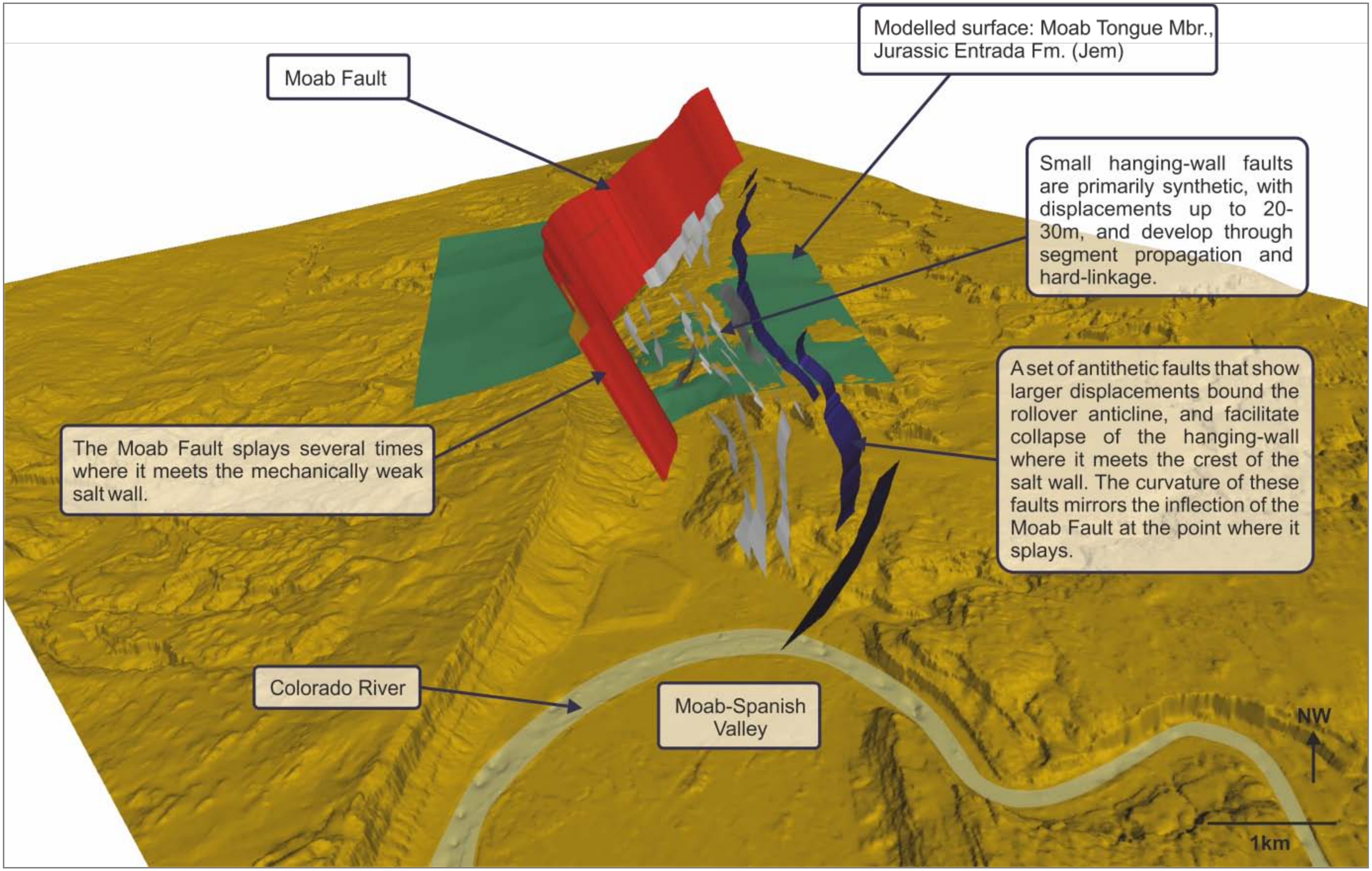

Figure 4. Preliminary structural model of the Moab Anticline at the northwest end of the Moab-Spanish salt-cored anticline based on field measurements, satellite image interpretation and published map information. A set of antithetic hanging-wall faults (blue) control collapse of the hanging-wall rollover into the crest of the salt wall.

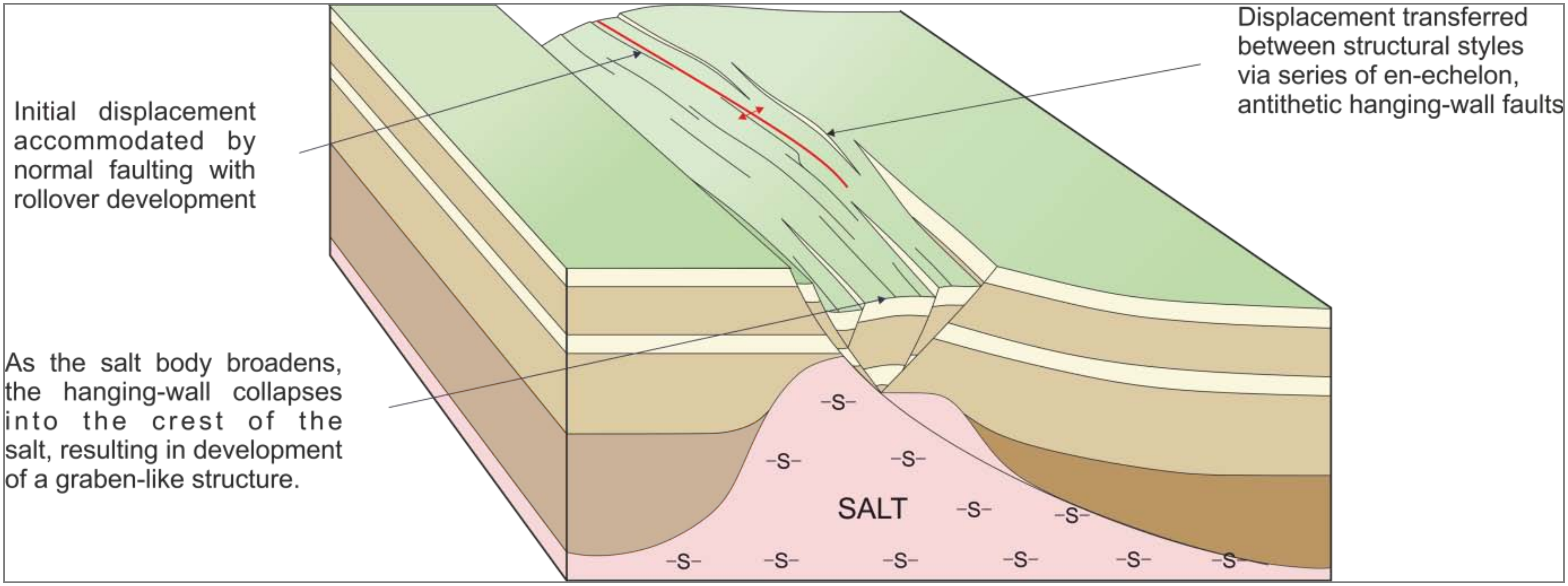

Figure 5. Typical geometry of fault system at the end of the Moab-Spanish salt-cored anticline. Rollover anticline plunges away from the salt. Where the rollover meets the salt body, collapse is facilitated by a graben-like geometry as the hanging-wall subsides into the salt.