Journal of the Geological Society, *London*, Vol. **163**, 2006, pp. 893–895. Printed in Great Britain.

Discussion on large sea, small tides: the Late Carboniferous seaway of NW Europe

Journal, Vol. 162, 2005, 417–420

Roger Higgs writes: Wells *et al*. (2005*a*,*b*) produced an innovative and thought-provoking numerical model of tides in the Late Carboniferous seaway of NW Europe, predicting very low tidal ranges (<1 m), consistent with the scarcity of sedimentary evidence for (weak) tides reported in the corresponding rocks. Based on the model, Wells *et al*. (2005*a*) argued intuitively that tidal range was minimum during (glacioeustatic) highstands, and maximum during lowstands (and transgressions). I would argue the converse.

During highstands, not only was the water volume (mass) greater, leading potentially to larger tides, but also any tide in the adjacent ocean would necessarily be passed into the seaway, adding to the locally generated tide. This is a weakness of the model: the oceanic tidal influence was 'not incorporated for simplicity' (Wells *et al*. 2005*a*, p. 418).

In contrast, during lowstands, the seaway became a freshwater lake (or chain of lakes), perched at the level of the outflow sill, and bordered by incised highstand prograded deltas and alluvial plains ('Lake Bude' of Higgs 1991, 2004). Disconnected from the global ocean, the lake would have had an extremely low tidal range (<5 cm), as in all lakes, because of the relatively small water volume (Talbot & Allen 1996). Indeed, no evidence for tides has been reported in Lake Bude deposits (Ross, Crackington and Bude Formations of Ireland and England; Higgs 1991, 2004, and references therein). However, given the (scarce) evidence reported elsewhere in the seaway, sedimentary structures indicative of weak tidal currents (e.g. ripples with foreset slack-water mud drapes; rhythmic lamination; opposed ripples) may eventually be discovered in the Lake Bude formations, probably associated with the volumetrically minor shale bands with brackish and marine fossils (Higgs 1991, 2004), representing transgressions and highstands, when Lake Bude was temporarily reconnected with the ocean, re-establishing a marine or nearly marine seaway.

Apart from this issue, two assumptions in the model are incorrect. First, the model assumes the seaway to have been everywhere shallow (<200 m). In fact, there was a deep-water flysch trough in the south, in a region where the tectonic setting was a north-verging foreland basin (e.g. Ziegler 1990, figs 14 and 15; Higgs 1991, 2004). The depth of water in the flysch trough could have exceeded 1 or 2 km, constituting a water mass that could affect the model's output significantly, both at lowstand and highstand. Second, there is said to be only 'Limited evidence of wave... processes' (Wells *et al*. 2005*a*, p. 419). On the contrary, the Bude and Ross Formations contain abundant evidence for storm waves, including hummocky cross-stratification and regional wave-planed surfaces (Higgs 1991, 2004).

3 April 2006

Martin R Wells, Peter A. Allison, Matthew D. Piggott, Christopher C. Pain, Gary, J. Hampson & Cassiano R. E. de Oliveira reply: We thank Higgs for his comments, and appreciate the opportunity to clarify the issues he raises. We used a new, 'next-generation' finite-element model (the Imperial College Ocean Model; ICOM) to estimate the range of the M_2 tidal constituent in an epi-continental seaway that covered much of NW Europe during the Late Carboniferous. Higgs raises three main points regarding the assumptions behind our application of the model, to which we respond below.

Impact of sea-level stand and degree of oceanic connection on tidal range. The tidal range of modern coastal seas is partly a reflection of astronomical forcing (astronomical tides) and partly a response of the movement and interaction of the ocean tide as it travels from the deep ocean to the adjacent shallow coastal sea (co-oscillating tides). Higgs argues that it is a weakness of our model that we only considered the astronomical tide within the European Late Carboniferous seaway. We believe that our treatment of tidal forcing is justified in this instance, because the palaeogeography of the seaway suggests that it was isolated from the open ocean. The Carboniferous basins of the UK, which formed part of the seaway, were isolated from the Palaeo-Tethys Ocean by the Variscan orogen to the south and via 2500 km of variably connected basins to the east. Equally, connection to the Panthalassa Ocean to the north was via 5000 km of tortuously arranged, narrow-necked marine and/or lacustrine basins (Ziegler 1990; Blakey 2004). It is highly unlikely that an oceanic tidal wave could have propagated over such large distances through these labyrinthine connections. By illustration, the modern Baltic Sea is located over 2000 km from the Atlantic Ocean and connected to the macro-tidal North Sea via the narrow, shallow and convoluted Kattegat and Belt Seas. As a result, the tidal bulge reaching the Baltic Sea is negligible and the (micro-)tidal range is almost entirely the result of astronomical forcing. Neither does the oceanic tidal bulge necessarily propagate into directly adjacent seas; for example, the modern Mediterranean Sea is directly adjacent to the Atlantic Ocean, but is joined via the narrow, shallow Strait of Gibraltar. Hence the (micro-)tidal range of the Mediterranean Sea is largely the result of astronomical forcing. Furthermore, the topographic barrier to the tidal wave does not have to be continuous; for example, there is a deep-water connection between the modern Gulf of Mexico and the Atlantic Ocean, but the islands between Florida and Mexico are sufficient to block the progress of the tidal wave from the ocean. ICOM simulation results of astronomical tides in the modern Mediterranean Sea compare well with the maximum tidal range documented from tide-gauge data (compare Wells *et al*. (2005*a*,*b*) with Kantha *et al*. (2001)). This quantitative test supports the observation that the contribution of co-oscillating tides to the modern Mediterranean Sea has a negligible impact on the maximum tidal range predicted, and demonstrates that the model can accurately reproduce astronomically forced tidal range. Although not used as a validation case study by Wells *et al*. (2005*a*,*b*), more recent work illustrates that ICOM accurately predicts astronomical tides in the modern Baltic Sea (Wells *et al*. 2007). Thus, we consider that the absence of co-oscillating tides from our simulations of the European Late Carboniferous seaway is justified and defensible.

On the basis that the water volume (mass) of the seaway and its degree of oceanic connection (and, thus, associated co-oscillating tides) would be greater during sea-level highstands, Higgs argues that a greater tidal range would be generated at such times. Although this makes intuitive sense, the reality is often more complex, as tidal range is also highly affected by resonance and shoaling in localized, shallow-water, coastal embayments (Dalrymple 1992). To test the impact of these competing mechanisms on tidal range, we considered two scenarios in our paper: (1) a sea-level highstand with larger water volume and connected basins along the seaway (fig. 2e of Wells *et al*. 2005*a*); (2) the early stages of a transgression following a sea-level lowstand, in which basins were not connected along the seaway (fig. 2f of Wells *et al*. 2005*a*). The latter scenario incorporated idealized, localized coastal embayments that mimic drowned fluvial valleys cut during the preceding lowstand. Such valleys are common in the stratigraphic record of the European Late Carboniferous seaway (e.g. Davies *et al*. 1999), and several contain estuarine fills (O'Mara *et al*. 1999; George 2001). The model results predict that tidal range was micro-tidal in both scenarios, but the largest tidal ranges were generated in localized coastal embayments in the 'early stages of transgression' scenario. This is despite a smaller water mass than the highstand scenario and is entirely due to funnelling and shoaling effects.

Bathymetry of the seaway. Higgs states that our model simulations assume 'the seaway to have been everywhere shallow (<200 m)', and thus neglected a deep-water flysch trough to the south (enclosure 15 of Ziegler 1990). The model simulations were designed to represent 'the highest sea level (stand) during the Namurian' (Wells *et al*. 2005*a*, p. 418), during which the marine connection between basins was greatest. Although not explicitly stated in our paper, we envisage this time interval to encompass the Kinderscoutian to Yeadonian (late Namurian, *c*. 318–315 Ma), when biostratigraphically distinctive marine bands had their most widespread extent in the seaway (e.g. Davies *et al*. 1999). By this time, the southerly flysch trough had been largely infilled, and the basin-fill strata comprise shallow-water deltaic and coal-bearing coastal plain deposits punctuated by seaway-wide marine bands (e.g. Hedeman & Teichmüller 1971; Davies *et al*. 1999; Hampson *et al*. 1999). Irrespective of the specific time interval represented in the simulations, we conducted a series of sensitivity tests for different average depths of the seaway. Although simulated tidal range increases with average basin depth, it remains definitively micro-tidal even at a seaway-wide depth of 500 m (<50 cm tidal range; fig. 2c and d of Wells *et al*. 2005*a*). These simulations of a 500 m deep seaway approximate the effects of incorporating a deep-water trough, and they demonstrate that the increased water volume in such a scenario is insufficient to significantly alter the tidal range.

Degree of wave influence in the seaway. Higgs contends that our statement that there is 'limited evidence of wave... processes' within the seaway deposits is incorrect, citing his own work in the Culm (SW England) and Clare (western Ireland) Basins in support (Higgs 1991, 2004). The degree of wave influence in the European Late Carboniferous seaway has little or no impact on our results; the simulations predict only tidal range. Furthermore, in the Culm Basin, the presence of wave-generated structures is not universally acknowledged (e.g. Burne 1998; Reading 1998). Equally, other workers in the Clare Basin have not described abundant wave- and storm-generated structures in either shallow-water or deep-water deposits (e.g. Pulham 1989; Elliott 2000; Martinsen *et al*. 2000). Although minor wave influence is noted in several other Carboniferous basins in the UK (e.g. South Wales Basin; Hampson 1998; George 2001), there is no dispute that the basin-fill successions are dominated by fluvial-dominated deltas (e.g. Collinson 1988; Pulham 1989). Therefore rather than construct a palaeobathymetry based upon contested interpretations (i.e. using storm- and wave-generated sedimentary structures as depth indicators) our sensitivity tests modelled a range of basin depths and all predicted slight tidal ranges. Therefore our conclusion that the seaway was micro-tidal remains valid.

6 June 2006

References

Blakey, R. 2004. Global plate tectonics and paleogeography. World Wide Web address: http://jan.ucc.nau.edu/rcb7/RCB.html.

Burne, R.V. 1998. Reply: Return of 'the fan that never was': Westphalian turbidite systems in the Variscan Culm Basin: Bude Formation (southwest England). *Sedimentology*, **45**, 970–975.

Collinson, J.D. 1988. Controls on Namurian sedimentation in the Central Province Basins of northern England. *In:* Besly, B.M. & Kelling, G. (eds) *Sedimentation in a Synorogenic Basin Complex: the Upper Carboniferous of Northwest Europe*. Blackie, Glasgow, 85–101.

Dalrymple, R.W. 1992. Tidal depositional systems. *In:* Walker, R.G. & James, N.P. (eds) *Facies Models: Response to Sea Level Change*. Geological Association of Canada, Toronto, Ont., 195–218.

Davies, S.J., Hampson, G.J., Flint, S. & Elliott, T. 1999. Continental-scale sequence stratigraphy of the Namurian, Upper Carboniferous and its application to reservoir prediction. *In:* Fleet, A.J. & Boldy, S.A.R. (eds) *Petroleum Geology of Northwest Europe: Proceeding of the 5th Conference*. Geological Society, London, 757–770.

Elliott, T. 2000. Depositional architecture of a sand-rich, channelized turbidite system: the Upper Carboniferous Ross Sandstone Formation, western Ireland. *In:* Weimer, P., Slatt, R.M., Coleman, J. et al. (eds) *Turbidite Reservoirs of the World*. 20th Annual Gulf Coast Section, SEPM, Bob F. Perkins Research Conference Proceedings, 342-373 (available on CD-ROM only).

George, G.T. 2001. Late Yeadonian (Upper Sandstone Group) incised valley supply and depositional systems in the South Wales peripheral foreland basin: implications for the evolution of the Culm Basin and for the Silesian hydrocarbon plays of onshore and offshore UK. *Marine and Petroleum Geology*, **18**, 671–705.

Hampson, G.J. 1998. Evidence for relative sea-level falls during deposition of the Upper Carboniferous Millstone Grit, South Wales. *Geological Journal*, **33**, 243–266.

Hampson, G.J., Stollhofen, H. & Flint, S.S. 1999. A sequence stratigraphic model for the Lower Coal Measures (Upper Carboniferous) of the Ruhr District, northwest Germany. *Sedimentology*, **46**, 1199–1232.

Hedeman, H.-A. & Teichmüller, R. 1971. The palaeogeographical development of the Upper Carboniferous. *Fortschritte in der Geologie von Rheinland und Westfalen*, **19**, 132–145.

Higgs, R. 1991. The Bude Formation (Lower Westphalian), SW England: siliciclastic shelf sedimentation in a large equatorial lake. *Sedimentology*, **38**, 445–469.

Higgs, R. 2004. Ross and Bude Formations (Carboniferous, Ireland and England): reinterpreted as lake-shelf turbidites. *Journal of Petroleum Geology*, **27**, 47–66.

Kantha, L.H., Pontius, P.E. & Anantharaj, V. 2001. Tides in marginal, semi-enclosed and coastal seas—part II: sea surface height. World Wide Web address: http://www.ssc.erc.msstate.edu/Tides2D/table_contents.html.

Martinsen, O.J., Walker, R.G. & Lien, T. 2000. Upper Carboniferous deep water sediments, western Ireland: analogs for passive margin turbidite plays. *In*: Weimer, P., et al. (eds) *Turbidite Reservoirs of the World*. 20th Annual Gulf Coast Section, SEPM, Bob F. Perkins Research Conference Proceedings, 533-555 (available on CD-ROM only).

O'Mara, P.T., Merryweather, M., Stockwell, M. & Bowler, M.M. 1999. The Trent Gas Field: correlation and reservoir quality within a complex Carboniferous stratigraphy. *In:* Fleet, A.J. & Boldy, S.A.R. (eds) *Petroleum Geology of Northwest Europe: Proceeding of the 5th Conference*. Geological Society, London, 809–821.

Pulham, A.J. 1989. Controls on internal structure and architecture of sandstone bodies within Upper Carboniferous fluvial-dominated deltas, County Clare, western Ireland. *In:* Whateley, M.K.G. & Pickering, K.T. (eds) *Deltas: Sites and Traps for Fossil Fuels*. Geological Society of London, Special Publications, **41**, 179–203.

Reading, H.G. 1998. Discussion: Return of 'the fan that never was': Westphalian turbidite systems in the Variscan Culm Basin: Bude Formation (southwest England). *Sedimentology*, **45**, 967–970.

Talbot, M.R. & Allen, P.A. 1996. Lakes. *In:* Reading, H.G. (ed.) *Sedimentary Environments: Processes, Facies and Stratigraphy*, *3rd*. Blackwell Science, Oxford, 83–124.

Wells, M.R., Allison, P.A., Piggott, M.D., Pain, C.C., Hampson, G.J. & De Oliveira, C.R.E. 2005a. Large sea, small tides: the Late Carboniferous seaway of NW Europe. *Journal of the Geological Society, London*, **162**, 417–420.

Wells, M.R., Allison, P.A., Hampson, G.J., Piggott, M.D. & Pain, C.C. 2005b. Modelling ancient tides: the Upper Carboniferous epi-continental seaway of Northwest Europe. *Sedimentology*, **52**, 715–735.

Wells, M.R., Allison, P.A., Hampson, G.J., Piggott, M.D., Pain, C.C. & Dodman, A. 2007. Investigating tides in the Early Pennsylvanian Seaway of NW Eurasia using the Imperial College Ocean Model. *In:* Holmden, C. & Pratt, B.R. (eds) *Dynamics of Epeiric Seas: Sedimentological, Paleontological and Geochemical Perspectives*. Geological Association of Canada, Special Publications, in press.

Ziegler, P.A. 1990. *Geological Atlas of Western and Central Europe*, *2nd*. Shell Internationale Petroleum, The Hague.

Roger Higgs, Geoclastica Ltd, 9 Jefferies Close, Marlborough SN8 1UB, UK (e-mail: rogerhiggs@geoclastica.com)

Martin R. Wells, Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

Peter A. Allison, Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK (e-mail: p.a.allison@imperial.ac.uk)

Matthew D. Piggott, Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

Christopher C. Pain, Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

Gary J. Hampson, Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

Cassiano R. E. de Oliveira, The George Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, USA

Scientific Editing by Rob Strachan