Note on paramoudra-like carbonate concretions in the Urenui Formation, North Taranaki: possible plumbing system for a Late Miocene methane seep field

C. Nelson[1], F. Schellenberg[1,2], P. King[3], B. Ricketts[4], P. Kamp[1], G. Browne[3], K. Campbell[4]

[1] Department of Earth Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand, Telephone 64-7-838-4698, Email c.nelson@waikato.ac.nz [2] Institut für Geologie und Paläontologie, Universität Tübingen, 72070 Tübingen, Germany [3] Geological and Nuclear Sciences, P.O. Box 30368, Lower Hutt [4] Department of Geology, University of Auckland, Private Bag 92019, Auckland

Abstract

A reconnaissance study of calcitic and dolomitic tubular concretions in upper slope mudstone of the Late Miocene Urenui Formation exposed along the north Taranaki coastline indicates that they have a complex diagenetic history involving different phases of carbonate cementation and likely hydrofracturing associated with build up of fluid/gas pressures. The concretions resemble classical paramoudra in the European chalk, but are not siliceous and do not have a trace fossil origin. Stable oxygen and carbon isotope data suggest that the micritic carbonate cements in the Urenui paramoudra were probably sourced primarily from ascending methane fluid/gases, and that they precipitated entirely within the host mudstone below the seafloor. We suggest the paramoudra may mark the subsurface plumbing networks of a Late Miocene cold seep system, in which case they have relevance to the evolution and migration of hydrocarbons in Taranaki Basin, at this site perhaps focussed along the Taranaki Fault. The presence of dislodged and mass-emplaced paramoudra in the axial conglomerate of channels within the Urenui mudstone suggests there could be a connection between the loci of seep field development and slope failure and canyon cutting on the Late Miocene Taranaki margin.

Introduction

Over the past decade or so, many studies of cold seeps in modern submarine environments from various tectonic settings have indicated the importance of carbonate formation associated with hydrocarbon seepage and bacterial activity (e.g., Camoin 1999). Authigenic carbonates interpreted as marking fossil cold seep sites have been less commonly reported (e.g., Campbell and Bottjer 1993; Peckmann et al. 1999; Aiello et al. 2001), but are important because they can provide a three-dimensional perspective of the shallow subsurface geometry of seep fields, as well as a temporal aspect to the study of seeps. Here we describe some preliminary results of an ongoing study of tubular (paramoudra-like) carbonate concretions in Miocene mudstone along the North Taranaki coastline. The concretions are interpreted to be sub-seafloor carbonate vent structures that mark sites of focussed fluid/methane gas escape from below, analogous to modern seafloor cold seeps, and consequently they may have implications for active petroleum system evolution in eastern Taranaki Basin.

Geologic setting

The Late Miocene (late Tongaporutuan) Urenui Formation in North Taranaki is a mid to upper slope mudstone that includes occasional fine sandstone, mudstone, and conglomeratic channel-fill units (Figure 1) (Faulconbridge 1994; King and Thrasher 1996). Coeval stratigraphic deposits are cyclothemic shelf sandstone, mudstone, and shellbeds of the Matemateaonga Formation, and base-of-slope and basin floor fan deposits of mudstone and sandstone comprising the deep-water Mount Messenger Formation (Kamp et al. 2002; King and Browne 2002). Collectively, the three formations represent a contiguous shelf-to-basin continental margin to eastern Taranaki Basin in the Late Miocene.

The Urenui Formation mudstone is typically massive to vaguely bedded, bioturbated, and weakly calcareous (<5% carbonate). Scattered carbonate concretions are common. Many of these concretions have conventional subspherical shapes, but in the well exposed coastal outcrops south of Pukearuhe Beach, in the vicinity of Mimi River and Wai-iti Stream (Figure 1), the mudstone shows a wide variety of additional concretionary structures, including pipes, tubes, slabs, and pockmark-like rings. Here we describe aspects of the carbonate pipes and tubes only (Figure 2), whose form and size resemble the paramoudra flint concretions from the Cretaceous chalk deposits in Europe that have been linked to concreted trace fossil burrows named *Bathichnus paramoudrae* (Bromley et al. 1975). A poster abstract by the Taranaki GSNZ (1994) has previously commented on the

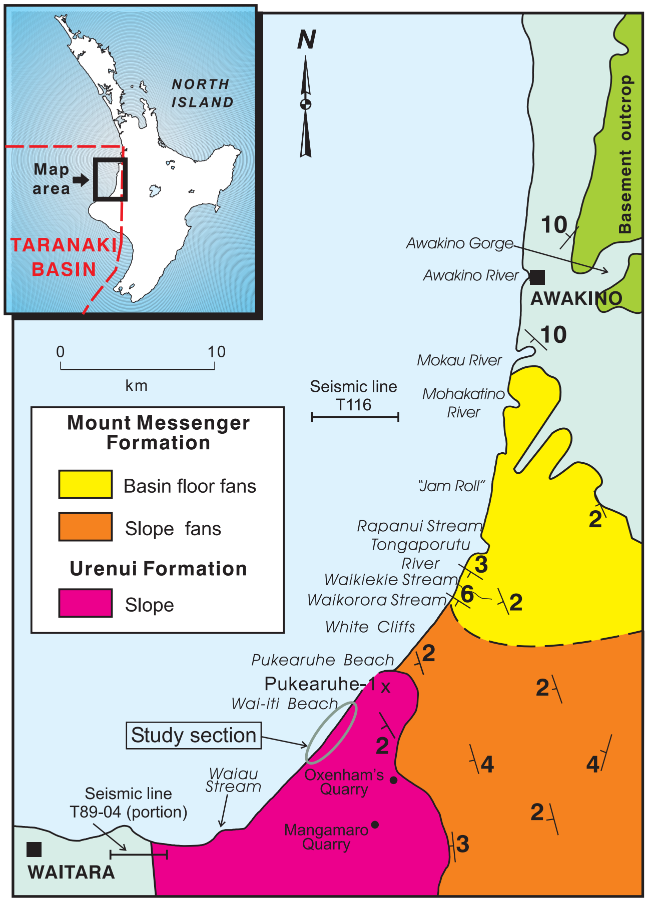

Figure 1. Locality and simplified geology map of the North Taranaki coastal region.

paramoudra-like nature of the Urenui tubular concretions, but did not consider their likely origin beyond a possible trace fossil association.

Paramoudra-like concretions

The paramoudra-like concretions are typically oriented vertically to subvertically, range in length from 0.5 to over 5.0 m, and in diameter from about 5 to 50 cm. They can appear segmented and may taper upwards or downwards, be sinuous or tortuous, and can branch, anastomose, or bend over, sometimes developing slab-like forms. Despite such wide variation, two main morphological groups of paramoudra-like concretions occur:

1 – Cylindrical, visibly up to 2 to 3 m long (limited by outcrop perspective) and 5 to 20 cm in diameter (Figure 2C). X-ray diffraction shows their cement is calcitic, ranging from low- to high-magnesium calcite.

2 – Bulbous, much larger and more irregular structures than group 1, being visibly up to 10 m long (the full height of the coastal cliff exposure) and up to 0.5 m or more across, with prominent annulated or pinch-and-swell external shapes (Figure 2A,B). Their cement is mainly dolomitic.

Most of the paramoudra-like concretions support a hole or conduit, 1 to 5 cm across, that runs the length of the structures at or near their centre (Figure 3A,B). Occasionally the single conduit is replaced by many central tubelets, each a few millimetres across. The conduits can be empty, or partly to completely filled by one or more generations of calcitic mineral precipitates or now lithified sediment. Sometimes a clear central conduit is not so evident, or is cryptic and marked by subtle colour changes in cross-sections of the concretionary structures (Figure 3C,D). Internal brecciation is a notable feature about the conduit of many of the bulbous paramoudra, and involves a crude radial arrangement of complex joints that tend to disappear outwards towards the margins of the paramoudra (Figure 3A-C). These fractures are healed by the same calcitic cements that precipitated within the central conduits (Figure 3B). Petrographic relationships indicate that multiple generations of fracturing and mineral cement precipitation characterise many of the paramoudra.

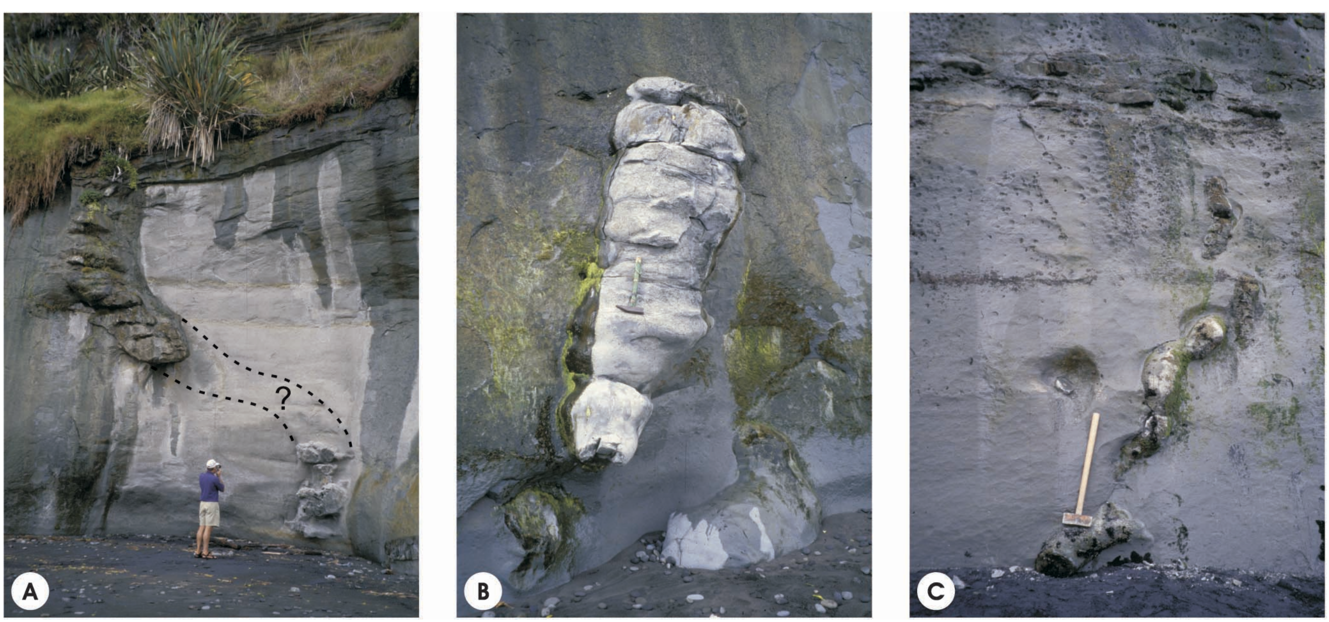

Figure 2. Examples of bulbous (A,B) and sinuous cylindrical (C) paramoudra-like concretions in Urenui mudstone.

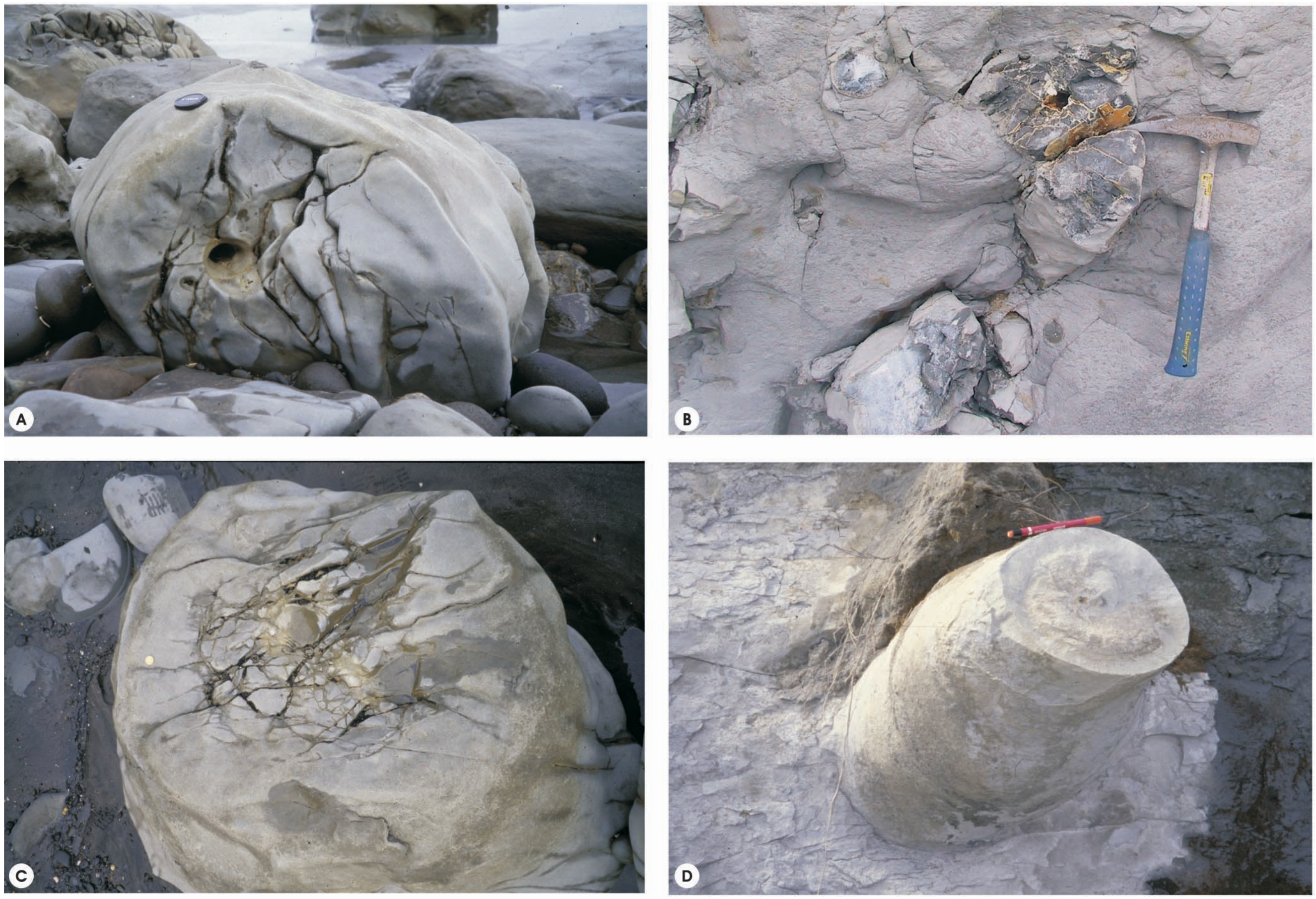

Figure 3. Examples of cross-sections of paramoudra from the Urenui mudstone showing open (A,B) and filled or more diffuse colour-banded (C,D) central conduits in bulbous (A,C) and cylindrical (B,D) varieties. Note the intensive internal fracturing and brecciation in A-C, healed by later calcite cement (most clearly evident here in B). Scales: A, lens cap; B, geological hammer; C, one dollar coin; D, pen.

Origin of paramoudra-like concretions

The carbonate content of the paramoudra ranges from about 30 to 75% (cf. <5% in the host sediment) and is due to precipitation of micrite or microsparite cement within the host mudstone, indicating the structures formed below the seabed. In the cylindrical paramoudra the cement is calcite, but in the bulbous paramoudra it is dolomite, suggesting they originated in different sub-seafloor environments or have different times of formation.

Stable oxygen and carbon isotopes can help interpret the nature and origin of the fluids that precipitated the carbonate cements forming the paramoudra (e.g., Nelson and Smith 1996). Preliminary results (Figure 4) indicate that the cluster of stable isotope values for the cylindrical paramoudra ($\delta^{13}C$ -40 to -30‰, $\delta^{18}O$ -2 to 0‰) is quite distinctive from that for the bulbous paramoudra ($\delta^{13}C$ -10 to +10‰, $\delta^{18}O$ +2 to +4‰). These isotope characteristics suggest calcite precipitation in the cylindrical paramoudra occurred within the microbial sulphate reduction zone from methane-derived CO_2 near below the seafloor, while dolomite precipitation in the bulbous paramoudra occurred in the deeper zone of methanogenesis, and was possibly later. Based on isotope relationships suggested by Roberts and Aharon (1994), the ultimate source of the carbon involved was predominantly deep thermogenic CH_4 and/or CO_2, or a mix of thermogenic hydrocarbons and shallower biogenic methane. Consequently, we suspect that the paramoudra may be delineating a shallow sub-seafloor plumbing system that focussed the upward ascent of methane gas/fluid flow towards the Urenui seabed in the Late Miocene. Interestingly, the paramoudra in the coastal section of North Taranaki lie directly above the strike of the Taranaki Fault, which possibly afforded an important escape route for the upward venting of hydrocarbons in the Late Miocene.

The isotope field encompassing the conduit and fracture-fill cements within the paramoudra is quite distinctive ($\delta^{13}C$ -4 to +20‰, $\delta^{18}O$ -6 to -2‰) from both the cylindrical and bulbous paramoudra concretionary carbonate groups (Figure 4). The isotope values are more compatible with a post-methanogenic origin for these cement fills from subsurface connate fluids, possibly involving also some fresh water influence.

Paramoudra and shelf margin instability

A characteristic feature of the Urenui Formation is the presence of large-scale channels nested within the slope mudstone and filled by coarser sediment, typically interbedded fine sandstone and siltstone (Faulconbridge

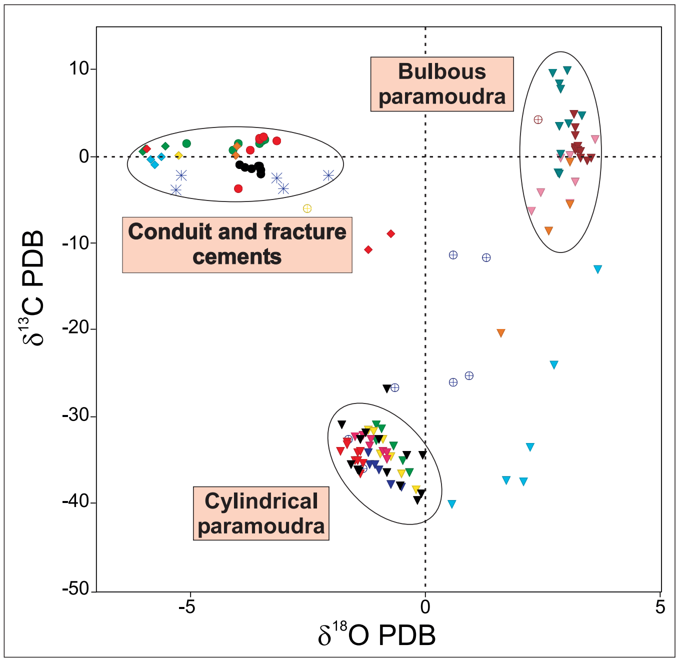

Figure 4. Summary $\delta^{13}C$ versus $\delta^{18}O$ cross-plot for the concretionary cement in several paramoudra samples, as well as some associated conduit/fracture cements, from the Urenui Formation. Note the distinctly separate clusters for each of the cylindrical paramoudra types, the bulbous paramoudra types, and the cements infilling the central conduits and/or fractures of the paramoudra. See text for interpretation of inferred diagenetic environments of cement precipitation.

1994). In several coastal localities the channel or canyon margins truncate *in situ* paramoudra within the mudstone. In particular, the lowest channel-fill deposit in the formation involves a mass-emplaced axial conglomerate (Whakarewa Conglomerate; King and Thrasher 1996) consisting of redeposited shelf shell hash (oysters, barnacles) and numerous disoriented, reworked cylindrical paramoudra concretions with their central conduits containing fine shell debris (Figure 5). It is possible that active fluid/gas venting and the growing seep field during Urenui sedimentation may have fostered localised shelf margin/upper slope instability

Figure 5. Axial fill of the mass-emplaced slope canyon conglomerate (Whakarewa Conglomerate) within the Urenui mudstone at Wai-iti Beach incorporates many dislodged and transported cylindrical paramoudra in a shell hash matrix.

and collapse, incorporating shelf fauna and the cylindrical paramoudra into the channel conglomeratic fill. The absence of bulbous paramoudra from the channel fill suggests either that sediment failure did not extend as deep as the sub-seafloor methanogenic zone or that the bulbous varieties formed mainly subsequent to shelf edge channelling.

Conclusions

1. The diverse types of paramoudra-like carbonate concretions in the Urenui Formation do not have a trace fossil origin, as has been suggested for the classical flint paramoudra in the European chalk.
2. The Urenui paramoudra have a complex diagenetic history: (a) Cylindrical types formed by cementation by calcitic micrite near below the seabed, probably in the sulphate reduction zone; (b) Bulbous types formed by cementation by dolomitic micrite, possibly in the deeper methanogenic zone; and (c) Subsequently, multiple generations of calcitic cements variably infilled the central conduits and/or brittle fractures in the paramoudra, the latter possibly resulting from hydrofracturing associated with pressure buildup as the central conduits of the paramoudra became increasingly constricted by mineral precipitation.
3. Cements in the paramoudra were probably ultimately sourced from ascending methane fluid/gases, and grew entirely within the host slope mudstone sediment.
4. The paramoudra may mark the subsurface plumbing networks of fossil cold seep systems, and consequently have relevance to the evolution and migration of hydrocarbons in Taranaki Basin, in this case perhaps up/along the Taranaki Fault.
5. A causal linkage may exist between the occurrence of paramoudra and the instigation of slope instability, failure and canyon cutting on the Late Miocene Taranaki margin.

References

Aiello, I.W, Garrison, R.E., Moore, J.C., Kastner, M. and Stakes, D.S. 2001. Anatomy and origin of carbonate structures in a Miocene cold-seep field. Geology 29: 1111-1114.

Bromley, R.G., Curran, H.A., Frey, R.W., Gutscheck, R.G. and Suttner, L.J. 1975. Problems in interpreting unusually large burrows. In: Frey, R.W. (Ed.), The Study of Trace Fossils. Springer-Verlag, New York. Pp. 351-376.

Camoin, G.F. (Ed.) 1999. Microbial Mediation in Carbonate Diagenesis. Special Issue Sedimentary Geology 126. Elsevier, Amsterdam.

Campbell, K.A. and Bottjer, D.J. 1993. Fossil cold seeps. National Geographic Research and Exploration 9: 326-343.

Faulconbridge, J. 1994. Sedimentology, Paleontology and Petrology of the Urenui Formation, North Taranaki. Unpublished MSc Thesis, University of Auckland, New Zealand.

Kamp, P.J.J., Vonk, A.J., Bland, K.J., Griffin, A.G., Hayton, S., Hendy, A.J.W., McIntyre, A.P., Nelson, C.S. and Naish, T. 2002. Megasequence architecture of Taranaki, Wanganui, and King Country basins and Neogene progradation of two continental margin wedges across western New Zealand. 2002 New Zealand Petroleum Conference Proceedings, p. 464-481.

King, P. and Browne, G. 2002. Miocene slope to basin-floor sequences exposed in North Taranaki, New Zealand. 2002 New Zealand Petroleum Conference Proceedings, p. 482-502.

King, P.R. and Thrasher, G.P. 1996. Cretaceous-Cenozoic Geology and Petroleum Systems of the Taranaki Basin. Institute of Geological and Nuclear Sciences Monograph 13.

Nelson, C.S. and Smith, A.M. 1996. Stable oxygen and carbon isotope compositional fields for skeletal and diagenetic components in New Zealand Cenozoic nontropical carbonate sediments and limestones: a synthesis and review. New Zealand Journal of Geology and Geophysics 39: 93-107.

Peckmann, J., Thiel, V., Michalelis, W., Clari, P., Gaillard, C., Martire, L. and Rietner, J. 1999. Cold seep deposits of Beauvoisin (Oxfordian; southeastern France) and Marmorito (Miocene; northern Italy): Microbially induced authigenic carbonates. International Journal of Earth Sciences 88: 60-75.

Roberts, H.H. and Aharon, P. 1994. Hydrocarbon-derived carbonate buildups of the northern Gulf of Mexico continental slope: A review of submersible investigations. GeoMarine Letters 14: 135-148.

Taranaki Geological Society of New Zealand 1994. Paramoudra/Zoophycos trace fossil association in the Miocene of the North Taranaki coast. Geological Society of New Zealand Miscellaneous Publication 80A: 175.

Acknowledgments

We thank Adam Vonk and Arne Pallentin (University of Waikato) for assistance with Figure production. We acknowledge the New Zealand Foundation for Research Science and Technology for research funding (contract UOWX0301)