Soft Sediment Carbonate Vein Networks in the Belt Purcell Rocks of Southeastern BC: A New Mode of Formation

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INTRODUCTION

The Belt Purcell Supergroup rocks extend from the Western United States into Southern British Columbia and Alberta. Soft sediment carbonate vein networks occur within various formations of the Belt Purcell rocks. These vein networks outcrop in various localities, however, this paper is limited to a description of the outcrops of the Kitchener Formation, west of Moyie Lake (Figure 1) in Southeastern British Columbia. These vein networks in the Purcell Range have been named Molar Tooth Structures (MTS) by Smith (1968) and that terminology is adopted here. This paper presents a hypothesis that the formation of MTS is the result of clathrate (gas-hydrate) destabilization. As gas hydrates destabilize, often explosively, they release considerable quantities of CO_2 gas and may also release abundant seismic energy. This model does not preclude the formation of MTS in a clathrate-poor environment, but proposes a geological environment that is consistent with both the gas bubble and seismic models of MTS formation. This model is also consistent with postulated Proterozoic atmospheric compositions and the observed absence of MTS in the Phanerozoic.

DESCRIPTION

At Moyie Lake, the MTS are best observed on the weathered surface, where they tend to weather recessively relative to the host carbonates. The MTS develop a whitish-grey weathered surface that contrasts with the tan coloured weathering of the host rocks (Photo 1). Both the MTS and the host carbonates have a similar medium grey colour on fresh surfaces. The dominant fill in the MTS are carbonates, which are generally authigenic and rarely clastic in origin (James *et al*., 1998). Authigenic pyrite and feldspar are found as accessory minerals within the MTS, attesting to fluid flow along these structures after initial infill by carbonate. Generally, the MTS are stratabound thin sinuous and/or linear vein-like structures occurring perpendicular to bedding, ranging up to a few centimetres in width which tend to pinch and swell. The MTS often appear to be folded, however, upon closer inspection, these fold-like structures are the result of syn-sedimentary deformation or a reflection of the complicated geometry of these interconnected MTS networks, or both (Photo 1).

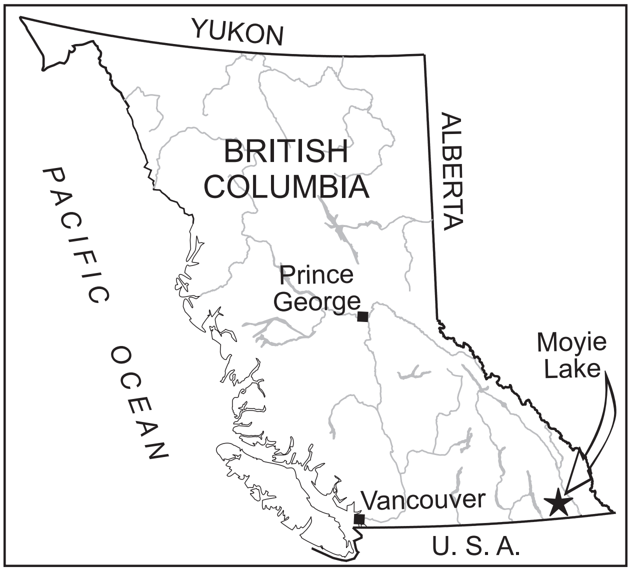

Figure 1. Index map showing the location of the MTS structures at Moyie Lake.

FORMATION OF MOLAR TOOTH STRUCTURES

The origin of carbonate MTS has long been an enigma in the geological community. These interconnected networks of carbonate veins are hosted within platformal Proterozoic carbonate rocks. Detailed studies by a number of workers have proposed two modes of formation for MTS. Some studies (Furniss *et al.*, 1998; Frank and Lyons, 1998) have shown that gas bubble expansion is a viable explanation for the formation of these

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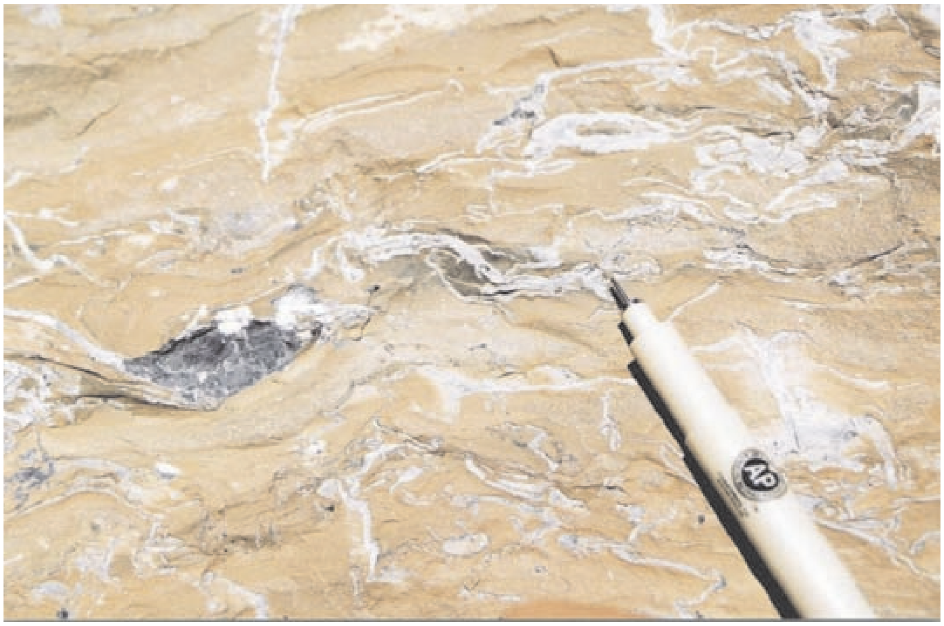

Photo 1. Molar Tooth Structure from the Belt Purcell Proterozoic carbonates at Moyie Lake, BC. The MTS is greyish-white on the weathered surface and a medium grey colour on the fresh surface (middle left of photo). The host carbonates weather a buff-tan colour. The tip of the pen points to an authogenic pyrite grain within the MTS.

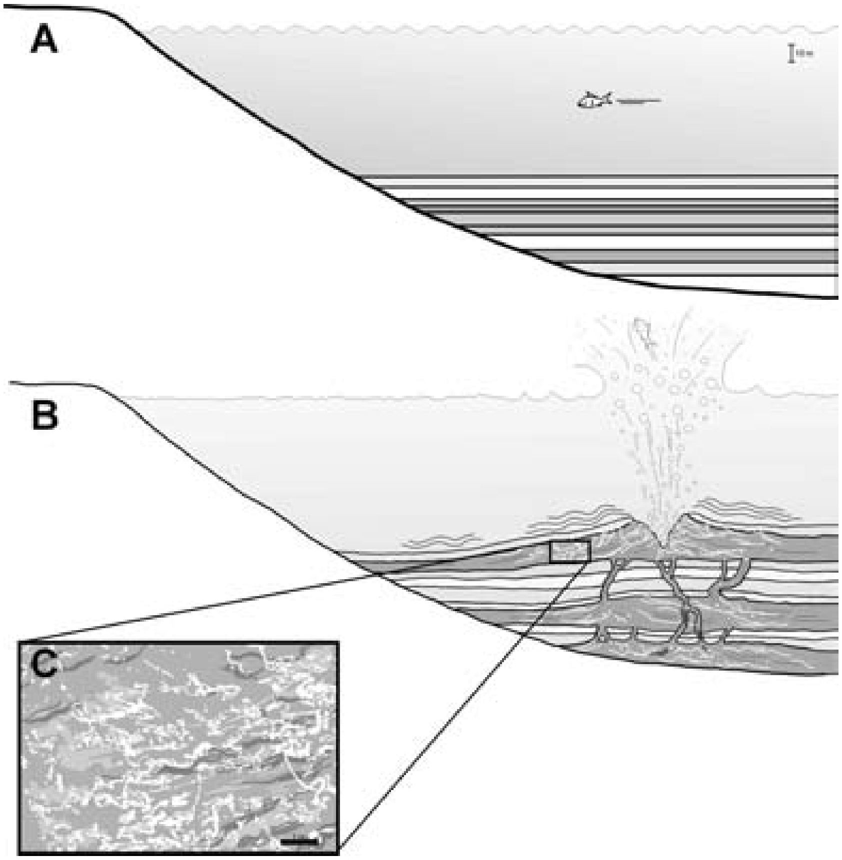

Figure 2. An idealized model of molar tooth formation via clathrate destabilization. A: a typical continental slope environment where clathrates can accumulate as part of the sedimentary column. B: destabilization of the clathrates leading to explosive conditions with volatile charged water and sediment columns in regions of abundant clathrate with more typical MTS found in the sediments with lesser clathrate concentrations. C: Idealized trace of MTS from outcrop similar to Photo 1. Actual MTS shown in white, bedding and structure within the Belt-Purcell carbonate are shown with greys.

structures, whereas other research (James *et al*., 1998; Pratt, 1998) on MTS worldwide has shown that MTS are limited to ramp and shallow platformal environments and formed during some sort of "seismic basinal event" accompanied, to varying degrees, by liquifaction and dewatering. In addition these studies have noted that MTS are limited in geologic time and occur exclusively in Proterozoic and older rocks.

Two major questions emerge from previous research: 1) is there a single geological environment that can readily produce the necessary conditions for both postulated modes of MTS formation, and 2) is there a reason why this geological environment existed during the Proterozoic and not since that time. This paper attempts to answer these questions by proposing that the MTS observed in Proterozoic platformal carbonate rocks are the result of the destabilzation of CO_2-clathrate contained within the platformal sediments and atmospheric changes from the Proterozoic to the Phanerozoic were less favourable to CO_2-clathrate stability.

Clathrates are solid solutions of H_2O and common gases, generally CO_2, CH_4, N_2, C_2H_6, O_2 Ar, NH_3 and H_2S (Bakker, 1998). There are two lattice forms of clathrate in which an expanded ice lattice traps gases in cage-like structures. One lattice type contains 46 H_2O molecules while the other has 136. These structures contain 8 and 24 gas cages respectively. Hydrates occur in many places on the Earth's surface, predominantly on the continental slopes, polar ice caps and permafrost areas. Their pressure-temperature stability fields vary depending upon composition, with the CH_4 and CO_2 clathrates being stable at the temperatures and pressures found on the continental slopes (Lerche and Bagirov, 1998; Booth *et al*., 1998). These clathrates occur as finely disseminated grains in sediment, nodules, thin layers and blocks. CO_2 clathrates have a more limited stability field than methane clathrates with destabilization occurring above 10 and 31°C respectively.

During the Proterozoic, Earth experienced its greatest change in atmospheric chemistry. The early Proterozoic atmosphere is thought to have contained predominantly CO_2, CO, H_2O and N_2 (Abelson, 1966) or possibly was a CH_4 dominant atmosphere (Oparin, 1953), whereas by the Cambrian Period, atmospheric compositions more closely resembled those found today (Kasting, 1993). Proterozoic atmospheric CO_2 concentrations were approximately 3 orders of magnitude higher than today (Kasting, 1993). This increased CO2 fugacity in the atmosphere would have resulted in increased CO_2 activity in the oceans as well.

In a simple system, in which two CO_2 bearing solids (clathrates and carbonates) compete for CO_2 in seawater, the precipitation of carbonate is represented by the reaction

$$Ca^{+2} + 2CO_3^{-2} \Leftrightarrow CaCO_3$$

This reaction is dependent upon pH as the production of the bicarbonate ion is related to the dissociation of carbonic acid (H_2CO_3),

$$H_2CO_3 \Leftrightarrow HCO_3- + H^+ \text{ and } HCO_3- \Leftrightarrow CO3^{-2} + H^+$$

with carbonic acid produced via the reaction

$$CO_2 + H_2O \Leftrightarrow H_2CO_3$$

The increased CO_2 content of the early atmosphere would have resulted in locally increased carbonic acid concentrations (and activities) near the atmosphere-seawater interface relative to today's conditions. This decreased pH (increased acidity) would lower the stability of calcite.

The formation of the CO_2 hydrate ($CO_2.5.75H_2O$) is not pH dependent and is based solely upon the availability of H_2O and CO_2, temperatures of less than 10°C, and pressures easily obtained below tens of metres of water or sediment. These pressure-temperature conditions are consistent with the James *et al*. (1998) depositional environment for MTS at or above storm wave-base. Thus it is conceivable that Proterozoic atmospheric conditions may have favoured the precipitation of clathrate as well as calcite.

The destabilization of clathrate is accompanied by a large volume increase and a corresponding energy release. Explosive destabilization of clathrate has been envoked to explain a large number of phenomena occurring on continental slopes, including: mud volcanoes; the disappearance of ships and aircraft in the Bermuda triangle; 350 meter diameter conical pockmarks on continental slopes, giant submarine landslides (USDOE, 1998), tsunamis (Discover, 2000) and "mistpouffers" which are distant explosion like sounds sporadically heard along the continental slopes of Europe and Atlantic Canada (USDOE, 1998).

A column of sediment with finely disseminated grains of clathrate could provide the necessary gas bubbles to form the MTS via the gas bubble formation model (Furniss *et al*, 1998). Sedimentary columns with larger amounts of destabilized clathrate would produce sufficient seismic energy to produce MTS (Figure 2) via the seismic MTS model (James *et al*., 1998; Pratt, 1998). Additionally, the presence of abundant CO_2 gas from clathrate destabilization could react with Ca and Mg in seawater to quickly form the carbonate infills commonly observed in MTS. This relatively rapid precipitation of calcite within the veins and the outflow of gas from the destabilized clathrate would inhibit clastic material from entering any of the cracks open to the sediment water interface and is consistent with the lack of clastic material within MTS. The limited appearance of MTS in the geological record (Figure 3) is also consistent with a clathrate destabilization model, as CO_2 was more abundant in the Earth's atmosphere up until the end of the Proterozoic.

The apparent peak in MTS formation near the end of the Proterozoic may be due to favourable CO_2 clathrate stability conditions associated with the specific CO_2/O_2 atmospheric ratio, the reduced development of continental slopes associated with supercontinent formation during the early Archean, or may be a function of younger rocks being preferentially preserved relative to older rocks.

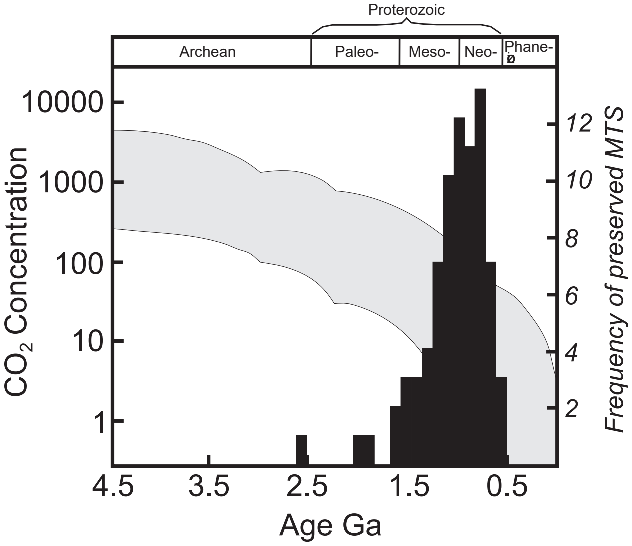

Figure 3. Histogram showing the frequency MTS occurrence (James *et al.,* 1998) vs. age (black) overlaying a plot of atmospheric CO_2 concentration (Kasting 1993) relative to present day atmosphere.

The clathrate model of MTS formation also offers some insight into the discussion of a CH_4 or CO_2 dominant atmosphere prior to the Cambrian. The clathrate model presented here is consistent with the model for a CO_2 dominant Proterozoic atmosphere, because a CH_4 dominant atmosphere would be more likely to precipitate methane clathrates on the continental slopes similar to modern day clathrate deposits. The abundance of CH_4 and lesser concentration of CO_2 would inhibit the precipitation of calcite and therefore not favour the formation of MTS.

CONCLUSIONS

Two models of Molar Tooth Structures are crack formation by gas bubble expansion and seismic shaking in platformal Proterozoic carbonate successions. This paper presents a model for MTS formation based on clathrate (CO_2-hydrate) destabilization that is consistent with the geological data for MTS and unites the two existing models into one geological environment. This model does not preclude the seismic or gas bubble models for MTS formation. It offers a possible mode of formation for MTS that is consistent with the seismic or gas bubble models, but does not preclude either model of MTS formation in the absence of clathrates. This model is also consistent with a pre-Phanerozoic CO_2 rich atmosphere.

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