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Late Devonian carbon isotope stratigraphy and sea level fluctuations, Canning Basin, Western Australia

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Abstract

The Upper Devonian reef complexes of the Canning Basin contain some of the world's best exposed, continuous stratigraphic sections through the Frasnian–Famennian boundary. The facies distribution and composition of these reef complexes record interactions among sea level changes, sediment supply, ocean chemistry, and paleoecology. Changes in relative sea level produced spatial shifts in reef platform development and regional changes in sediment supply that can be correlated across facies boundaries using a combination of sequence stratigraphy, biostratigraphy, and carbon isotope stratigraphy. During the lowstand interval below the Frasnian–Famennian boundary, the reef margin advanced down the reef slope in shallow-water environments, and siliciclastics locally dominated in the margin slope environment. Compilation of a broad late Frasnian to early Famennian sequence stratigraphic framework for the Canning Basin demonstrates that transgressive intervals correlate to positive carbon isotopic excursions within the basin. These isotopic shifts also can be correlated to time-equivalent positive carbon isotopic excursions reported from transgressive intervals in Europe. Thus, the late Frasnian transgressions in the Canning Basin were primarily eustatic rather than tectonic in origin, and positive carbon isotopic signatures of the Kellwasser horizons are globally correlative.

Keywords: Late Devonian; isotopes; Canning Basin; stratigraphy

1. Introduction

The use of sequence stratigraphy, chemostratigraphy, and biostratigraphy allows detailed correlation among diverse stratigraphic sections while simultaneously providing insights into critical periods of Earth's history, such as the Late Devonian mass extinction. The Frasnian–Famennian boundary marks one of the five major extinctions of the Phanerozoic (Sepkoski, 1996) and has been a major focus of Late Devonian stratigraphic and geochemical studies (Becker et al., 1993; Geldsetzer et al., 1993; Joachimski and Buggisch, 1993; Kennard et al., 1992; Playford et al., 1984; Southgate et al., 1993; Wang et al., 1996; Joachimski et al., 2002). Sea level changes have been proposed as contributing factors to mass extinctions (Copper, 1986; Thompson and Newton, 1988; Joachimski and Buggisch, 1993; Hal-

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lam and Wignall, 1999). However, interpretations of sea level changes across the Frasnian–Famennian boundary vary substantially (Kennard et al., 1992; George et al., 1997; Hallam and Wignall, 1999).

Correlating third-order and higher sea level changes in the Canning Basin is difficult due to variations in facies composition, rarity of sequence-defining unconformities, and lack of biostratigraphic fossils in shallow reef environments. Variability in time-equivalent facies can be due to heterogeneities in reef growth (Ward, 1999) and localized depocenters of siliciclastics (Holmes and Christie-Blick, 1993). Correlation of the Kellwasser horizons of Europe to equivalent strata in the Canning Basin have not been successful due to a lack of upper Frasnian black shale horizons in the Canning Basin (Becker et al., 1991). In the Canning Basin conodont and goniatite biostratigraphies have locally provided a basis for regional and global correlation (Nicoll, 1984; Becker and House, 1997; George et al., 1997; George and Chow, 2002). However, these fossils are most abundant in deep-water facies and rarely found in back-reef and reef margin environments (Nicoll, 1984), which makes biostratigraphic correlation of reef platforms to basinal facies very difficult if not impossible. Regional and global correlation of third-order sequences also may be hampered by local tectonic effects. Hall (1984) suggested that tectonic activity in the Canning Basin was locally subsiding by Late Devonian time. However, Southgate et al. (1993), Holmes and Christie-Blick (1993), and Ward (1999) cite tectonic activity as a potential origin for some of their sequences.

Second- and third-order sea level interpretations for the Upper Devonian reef complexes in the Canning Basin are based on shifting facies patterns, rare exposure surfaces, and seismic stratigraphy (Playford et al., 1989; Southgate et al., 1993; Whittam et al., 1994; George et al., 1997; Ward, 1999). As a whole, the Upper Devonian reef complexes of the Canning Basin are interpreted as a second-order sequence, because the reef platforms back-stepped during Frasnian time and prograded during Famennian time (Playford, 1980). Although the second-order sea level interpretation is widely accepted, third-order sequence stratigraphic models are more controversial (Southgate et al., 1993; Holmes and Christie-Blick, 1993; Whittam et al., 1994; Becker and House, 1997; George et al., 1997; Ward, 1999). Based on seismic stratigraphy and well log data, Southgate et al. (1993) proposed 18 third-order sequences for upper Devonian to Tournaisian subsurface strata in the Canning Basin. Becker and House (1997) also found evidence for sea level changes in deep-water strata but did not link these changes to previously interpreted third-order sequences. Whittam et al. (1994) extended seven of Southgate et al.'s (1993) subsurface sequences to various outcrops in the northern Canning Basin, using rare exposure surfaces and shifting facies patterns. Their correlations, however, have been criticized for lack of time control (Becker and House, 1997). The subsurface interpretations differ from the third-order sequences defined by George et al. (1997) for a stratigraphic section at Dingo Gap. Holmes and Christie-Blick (1993) and Ward (1999) recognized probable third-order sequences in the Van Emmerick Range, at Stony Creek, and in the Napier Range but expressed uncertainty in correlating their sequences to pre-existing sequence stratigraphic frameworks.

Carbon isotope stratigraphy is based on time-equivalent changes in ^{13}C:^{12}C ratios and can serve as a powerful tool for stratigraphic correlation. Global changes in the carbon isotopic values of seawater at the time scale of $>10^5$ years are due to long-term variations in carbon burial, continental weathering, sea surface temperature, and ocean pH (Lynch-Stieglitz et al., 1995; Spero et al., 1997; Kump and Arthur, 1999). Shorter-term variations may be due to fluctuations in primary productivity, the release of methane clathrates, or changes in ocean circulation (Kump, 1991; Haq, 1998; Kump and Arthur, 1999; Spero and Lea, 2002). Closed or silled basins, which are not fully equilibrated with ocean water, may show carbon isotopic variations independent of the global isotopic curve, but basins with good circulation reflect global $\delta^{13}C$ variations.

Thus, carbon isotope stratigraphy provides a basis for global correlations. For example, Neoproterozoic strata have been correlated using large swings in $\delta^{13}C$ (Kaufman and Knoll, 1995; Hoffman et al., 1998), and $\delta^{13}C$ variations have been used locally to correlate basinal to reef platform facies in Cretaceous reef complexes (Grotsch et al., 1998; Ferreri, 1997). A $\delta^{13}C$ curve for upper Frasnian to lower Famennian strata has already been defined from European, North American, and Australian stratigraphic sections (Joachimski and Buggisch, 1993; Wang et al., 1996; Joachimski et al., 2002). This $\delta^{13}C$ curve has two positive excursions and may be used as a tool for regional and global stratigraphic correlation. During Late Devonian time, the Canning Basin contained reefs with cosmopolitan fauna, suggesting that the water within the basin had normal salinity and circulated with the ocean (Becker et al., 1991 and references therein). In the Canning Basin, carbon isotope curves have been measured from deep-water strata at McWhae Ridge and Casey Falls and have been correlated to Upper Devonian carbon isotope curves from Europe and North America (Joachimski et al., 2002). The $\delta^{13}C$ variations observed from deep-water strata can be used for intrabasinal correlation to shallower water facies.

This study shows that carbon isotope stratigraphy, accompanied by the available biostratigraphy and sequence stratigraphy, can serve as a powerful tool for stratigraphic correlation in the Canning Basin. By using detailed $\delta^{13}C$ curves, sedimentary indicators of sea level change from different locations are correlated to produce a refined sequence stratigraphic framework for the Canning Basin. Carbon isotopic correlations allow comparison of the Canning Basin relative sea level curve to late Frasnian–early Famennian global sea level interpretations.

2. Geologic setting

The northern edge of the Canning Basin was located about 15° south of the equator during Middle to Late Devonian time and was ideally situated for reef building processes (Playford, 1980; Hurley, 1986). Termed the Devonian 'Great Barrier Reef', the 350-km northwest–southeast-trending Givetian to Famennian reef complexes provide an unparalleled view of Late Devonian reef life and reef development (Fig. 1). During Late Devonian time, the Canning Basin was an extensional basin with high subsidence rates (Holmes and Christie-Blick, 1993; Southgate et al., 1993) that accommodated over 2 km of Devonian strata (Brown et al., 1984).

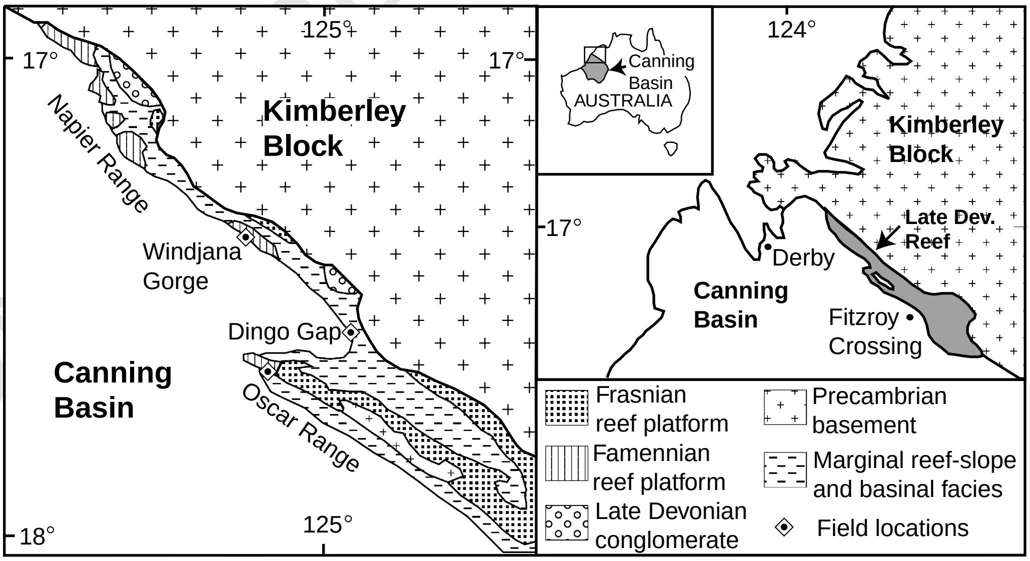

Fig. 1. Location and general geology of field area. Modified from Kerans et al. (1986).

Stratigraphic nomenclature for division of reef facies was defined by Guppy et al. (1958), Playford and Lowry (1966), and Playford (1980). Platform facies are recognized as horizontal beds of mostly carbonate in a shallow-water depositional environment. The reef margins are discontinuous, massively bedded framestones and bindstones at the edge of the reef platforms. Marginal slope facies are recognized by steep depositional dips and are situated between platform and basinal facies. Frasnian platform facies comprise the Pillara Formation (Playford, 1980). The back-reef subfacies of the Famennian platform strata are the Nullara Formation, and Famennian reef margin and reefal slope subfacies comprise the Windjana Limestone (Playford, 1980). The Napier Formation is composed of both Frasnian and Famennian marginal slope strata (Playford, 1980).

3. Methods

Three areas were examined for this study, the Oscar Range, Windjana Gorge, and Dingo Gap (Fig. 1). Long stratigraphic sections (> 100 m) were measured for broad trends in sedimentology and carbon isotopic values. Shorter sections were measured at specific areas of interest. Available biostratigraphic and sequence stratigraphic data were used for preliminary stratigraphic correlation. At Windjana Gorge a 245-m section was measured at the eastern end of the gorge and a 44-m section was measured across the Frasnian–Famennian boundary in the 'classic face' area of the gorge (Playford, 1980). At Dingo Gap, the lower part of George et al.'s (1997) section was remeasured to produce a 236-m section, and a 57-m section was measured in the Dingo Gap back-reef area, described by Ward (1996, 1999). At the northwestern tip of the Oscar Range, two stratigraphic sections were measured and combined to form a 106-m section. In all stratigraphic sections, samples were collected at regular intervals of about 10 m with higher-density sampling around the Frasnian–Famennian boundary.

3.1. Laboratory methods

Samples collected from the field were made into thin sections and were screened with both standard and cathodoluminescent microscopy. $\delta^{13}C$ sampling focussed on micrites, early marine cements, and brachiopods with well-preserved petrographic textures and little to no luminescence. In peloidal packstones and wackestones, micrite samples were obtained from clusters of micritic peloids within a micrite matrix. $\delta^{13}C$ values associated with siliciclastic-rich strata were obtained from brachiopods and peloidal grainstone–packstone beds intercalated within the sandier lithofacies. Early marine cements, such as radiaxial fibrous calcites and fine-bladed calcites, were sampled where available. Powders for carbon isotope analyses were drilled either from thin section billets using a standard drill press with a 0.75-mm diamond drill bit or from thin sections using an automated Merchantek microdrill with a 10-μm drill tip. Samples were roasted under vacuum for 1 h at 350°C in order to remove organic carbon. Stable isotope analyses were performed on a Fisons Optima isotope ratio mass spectrometer using an Isocarb common acid bath at 90°C at the University of California, Davis. Analytical precision of both carbon and oxygen isotopic analyses is better than ±0.1‰ (2σ). $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to VPDB.

4. Results and interpretations

4.1. Sedimentology

The long stratigraphic sections of this study, measured at Dingo Gap, eastern Windjana Gorge, and the Oscar Range, can be roughly correlated using regional facies tracts and biostratigraphy. The late Frasnian reefs in the Napier Range developed as three back-stepping platforms, which can be correlated regionally (Ward, 1999). The long sections at Windjana Gorge and Dingo Gap begin in or on top of Ward's (1999) platform B. The long section from the Oscar Range begins at the second to last reef platform identified by Hurley (1986).

This reef platform also has a back-stepping morphology and may correlate to platform B in the Napier Range. The three long sections and the classic face section pass through the Frasnian–Famennian boundary. In the Windjana Gorge east and classic face sections, conodont dating identifies the Frasnian–Famennian boundary within a 0.5-m interval (P. Playford, 1999, personal communication). Conodont dating from the Dingo Gap section places the Frasnian–Famennian boundary within a 7-m interval (George et al., 1997), and the Frasnian–Famennian boundary in the Oscar Range is placed at an unconformity that truncates beds containing the last occurrence of Frasnian stromatoporoids (Hurley, 1986).

The northwestern Oscar Range has excellent exposures of upper Frasnian and lower Famennian strata. In the outcrops where sections were measured, Famennian strata grade laterally from back-reef to reef margin facies. An unconformity is present at the Frasnian–Famennian boundary in the Oscar Range and in some locations is reported to have physical relief of at least 1–2 m (Hurley, 1986). The northern Oscar Range has very little siliciclastic sediment, possibly due to paleogeographic separation of the reef from the mainland (Playford et al., 1989), (Fig. 1). Based on reef geometries, Hurley (1986) classified the two Frasnian reef platforms observed in this study as back-stepping and advancing (Fig. 2). In the Oscar Range section (Fig. 2), Frasnian strata consist of alternating reef platforms and intervals of upper marginal slope facies. The Frasnian reef platforms are massively bedded, stromatoporoid framestones with some corals, some brachiopods, and abundant renalcids. Both massive and branching stromatoporoids were observed, and many are in up-right growth position. The Frasnian upper marginal slope facies consist of medium to thickly bedded, peloidal grainstones and packstones, containing transported stromatoporoids, brachiopods, crinoids, sponges, and rare nautiloids. Depositional dips of these beds were approximately 25°, based on geopetal indicators of stratigraphic up. In some cases, filamentous algal fossils are observed and probably bound the marginal slope sediment. Famennian back-reef strata are well bedded, peloidal grain-

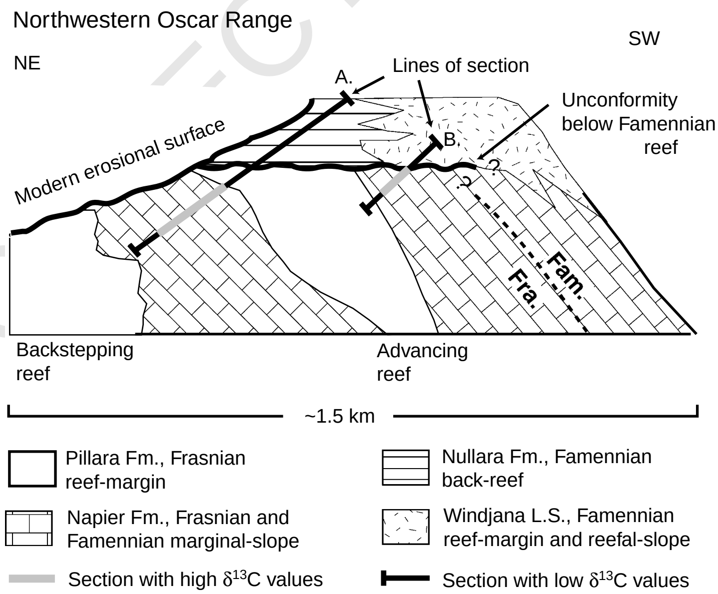

Fig. 2. Interpretive diagram of reef complex at northwestern tip of Oscar Range. Reefs were interpreted as advancing and back-stepping by Hurley (1986). Strata in section B contain an interval of high $\delta^{13}C$ values, which are missing from section A. Sections A and B were combined for Figs. 5 and 6. Position of the unconformity and placement of the Frasnian–Famennian boundary in the marginal slope strata are uncertain.

stones and wackestones with ooids, oncoids, and fenestral porosity. Famennian reef margin and reef flat rocks consist of massively bedded, microbial bindstones and framestones.

The back-reef section measured at Dingo Gap spans a back-stepping interval identified by Ward (1999) (Fig. 3). In the back-reef strata, beds alternate between stromatoporoid framestones, peloidal grainstones, and fenestral wackestones in 2–4-m shallowing upward intervals. These strata are similar to those described at Windjana Gorge by Wood (2000) and in the Pillara Range by Read (1973). The middle of the Dingo Gap back-reef section is interrupted by reef margin facies, which consists of massively bedded stromatoporoid framestones. These beds are difficult to trace laterally and may be composed of multiple isolated bioherms. Above the bioherms, marginal slope strata onlap the reef margin subfacies, and the reef platform has a back-stepping morphology (Fig. 3).

Stratigraphic sections through marginal slope facies were measured at Dingo Gap and Windjana Gorge. Measured depositional dips of these beds vary from 15° to 45° (Playford and Hocking, 1999). The Dingo Gap marginal slope section starts in the Frasnian reef margin at a stratigraphic horizon, which can be physically traced to the Dingo Gap back-reef section (Fig. 3). Stratigraphically above the reef margin lie approximately 30 m of coarse reef breccias, which have been interpreted as a product of reef collapse (George et al., 1997). Near the Frasnian–Famennian boundary, several bioherms and/or allochthonous reef blocks are associated with beds of grainstone and reef breccia, which correspond to George et al.'s (1997) lithofacies one. George et al. (1997) describe a large bioherm below the Frasnian–Famennian boundary, which consists of corals, sponges, and stromatoporoids. However, many large blocks above and adjacent to this bioherm have geopetal indicators suggesting transport. Many of the allochthonous blocks and/or bioherms are topped by in situ deep-water stromatolites (George, 1999). A prominent 2 m thick, brachiopod rudstone passes just below the Frasnian–Famennian boundary and is laterally traceable along strike for at least 100 m in both directions. The lower Famennian strata of the Dingo Gap section grade from packstones and grainstone to coarse quartzofeldspathic sandstone. The slightly sandy, thinly bedded, oolitic grainstones correspond to George et al.'s (1997) lithofacies two, and the carbonate-rich strata in the marginal slope section at Dingo Gap comprise the Kalmanyi Member of the Napier Formation (Playford and Hocking, 1999). At the top of the section, sandstone beds, with some ooid-rich intervals and allochthonous reef blocks, correspond to the base of the Tarakalu Member of the Napier Formation (Playford and Hocking, 1999) and George et al.'s (1997) lithofacies three. Locally, the brachiopod-rich bed, allochthonous blocks, and bioherms were partially dolomitized.

Two marginal slope sections were measured at Windjana Gorge, a long section at the eastern end and a short section across the Frasnian–Famennian boundary in the 'classic face'. At the eastern end of Windjana Gorge, the marginal slope strata consist of alternating carbonate and siliciclastic intervals (Fig. 4). The base of the eastern section begins in reef platform B (Ward, 1996), which is stromatoporoid framestone with some sponges and renalcids. The reef platform is overlain by approximately 15 m of coarse reef breccia. Of the two major carbonate-rich intervals, a 50-m interval lies above the coarse reef breccia, and a 35-m interval spans the Frasnian–Famennian boundary. They consist of packstones and grainstones with some thin reef breccia beds. The siliciclastic beds consist of siltstones and very fine quartzofeldspathic sandstones with occasional 0.5–1 m thick interbeds of reef breccia. Large allochthonous reef blocks and possibly some bioherms also are present near the Frasnian–Famennian boundary. The allochthonous reef blocks are angular and have geopetal indicators suggesting transport. A brachiopod rudstone lies just under the Frasnian–Famennian boundary. The rudstone consists of several brachiopod-rich lenses and has a composition similar to the brachiopod rudstone from Dingo Gap. Above the brachiopod rudstone, a 2 m thick bed of red siltstone/fine sandstone contains possible stromatolites. At the Frasnian–Famennian boundary, no evidence for an unconformity exists in marginal slope subfacies at Windjana Gorge. Famennian strata grade

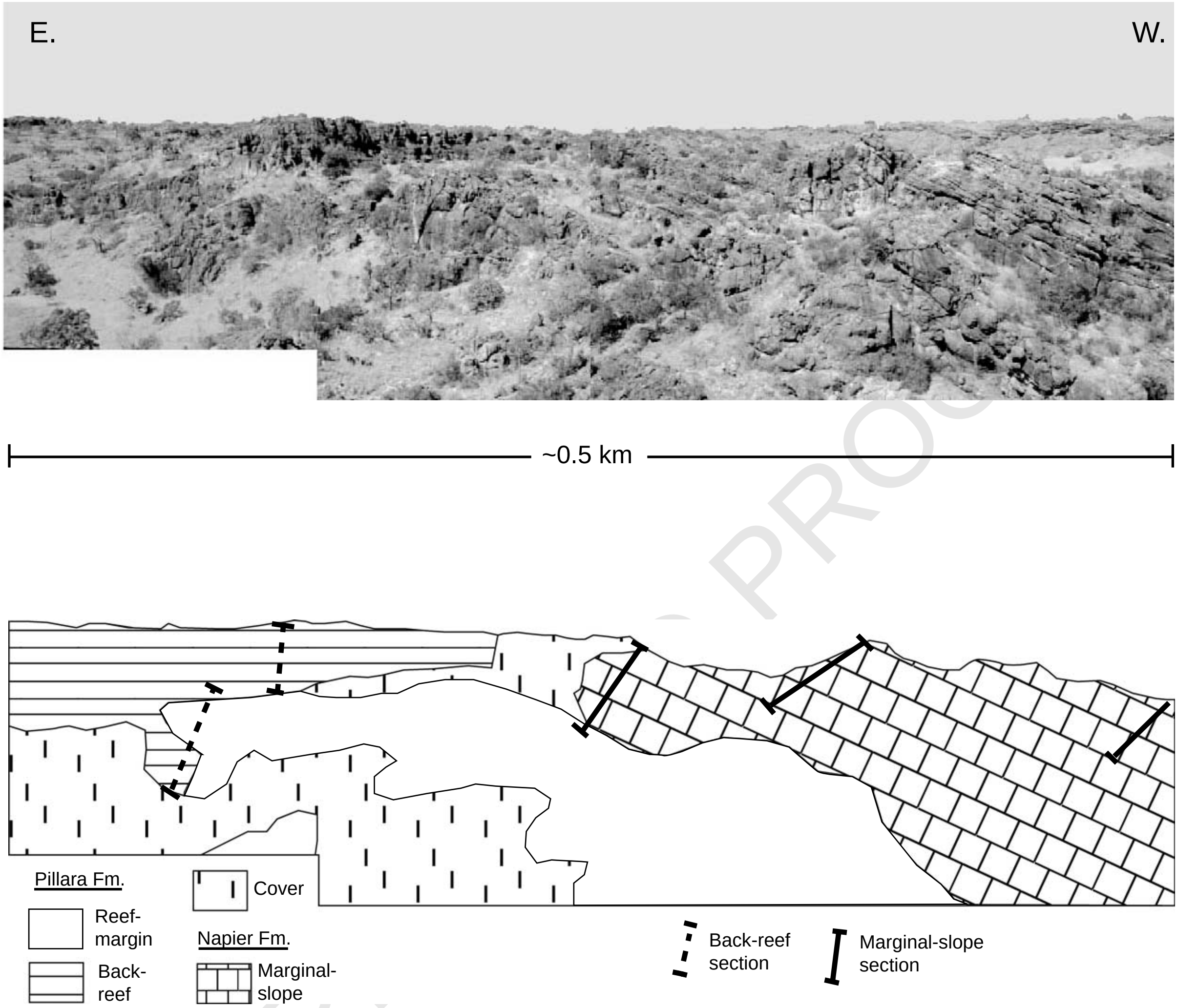

Fig. 3. Photomosaic and sketch of strata at Dingo Gap. See Figs. 5 and 6 for stratigraphic columns.

from peloidal grainstone and packstones to coarse quartzofeldspathic sandstones. The sandstone beds at the top of the eastern Windjana Gorge section are stratigraphically equivalent to the Tarakalu Member at Dingo Gap.

In the ‘classic face’ section, the strata are almost entirely carbonates and do not contain the thick intervals of siliciclastic strata observed in the eastern section. The Frasnian–Famennian boundary is at the contact of a brachiopod rudstone and a recessive 0.5 m thick siltstone. A bioherm or allochthonous block also is present just below the Frasnian–Famennian boundary in the classic face section. Patchy dolomitization was observed locally in both Windjana Gorge sections. Generally, the limestone is well preserved and usually non-luminescent in thin section.

4.2. Stratigraphic interpretation

In the measured sections, variations in facies composition and spatial shifts of facies through time are the basis for interpretations of sea level fluctuations. Sequence stratigraphic models of reef

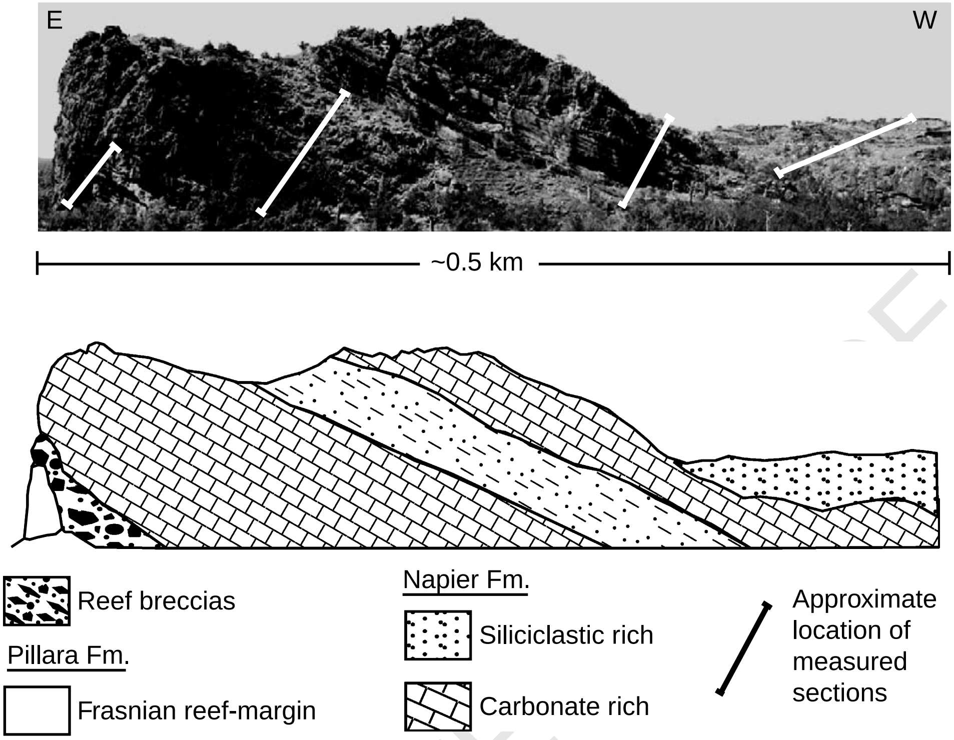

Fig. 4. Photomosaic and sketch of strata at the eastern end of Windjana Gorge. See Figs. 5 and 6 for stratigraphic columns.

development predict that the position of the reef margin changes with respect to fluctuations in relative sea level (Handford and Loucks, 1993). Therefore, alternating intervals of reef margin and upper marginal slope facies at the northwestern tip of the Oscar Range are interpreted as sea-level-driven (Figs. 2 and 5). In the stratigraphic column, reef margin facies represent highstand to lowstand conditions, and upper reef slope facies represent two late Frasnian transgressive intervals. A sequence boundary corresponds to the Frasnian–Famennian boundary in the Oscar Range, and a second sequence boundary is interpreted below a lowstand reef margin (Fig. 5). Back-stepping events in the Frasnian reef platform at Dingo Gap and Windjana Gorge also were due to rises in relative sea level (Playford et al., 1989; Ward, 1999). Similar sea-level-driven facies patterns have been observed in the Tertiary reef strata of the Bahamas platform margin, where prograding reef framestones correspond to lowstand to highstand conditions and are overlain by transgressive upper marginal slope strata (Kenter et al., 2001).

In the marginal slope facies, changes in lithology may reflect changes in relative sea level. Reciprocal carbonate–siliciclastic sedimentation at the eastern end of Windjana Gorge is interpreted as sea-level-driven. Sequence stratigraphic models predict that during transgressive to highstand intervals siliciclastic sediments are deposited farther shoreward on the shelf and carbonate sedimentation dominates the reef slope (Handford and Loucks, 1993). Conversely, during lowstand conditions the carbonate factory shuts down, siliciclastic sediments breach the reef platforms, and siliciclastic deposition dominates the reef slopes (Handford and Loucks, 1993). Based on seismic stratigraphy and core logs, reciprocal sedimentation is documented in subsurface stratigraphy in the Canning Basin (Southgate et al., 1993). Holmes and Christie-Blick (1993) have observed possible evidence for reciprocal sedimentation in outcrop in the Van Emmerick Range and at

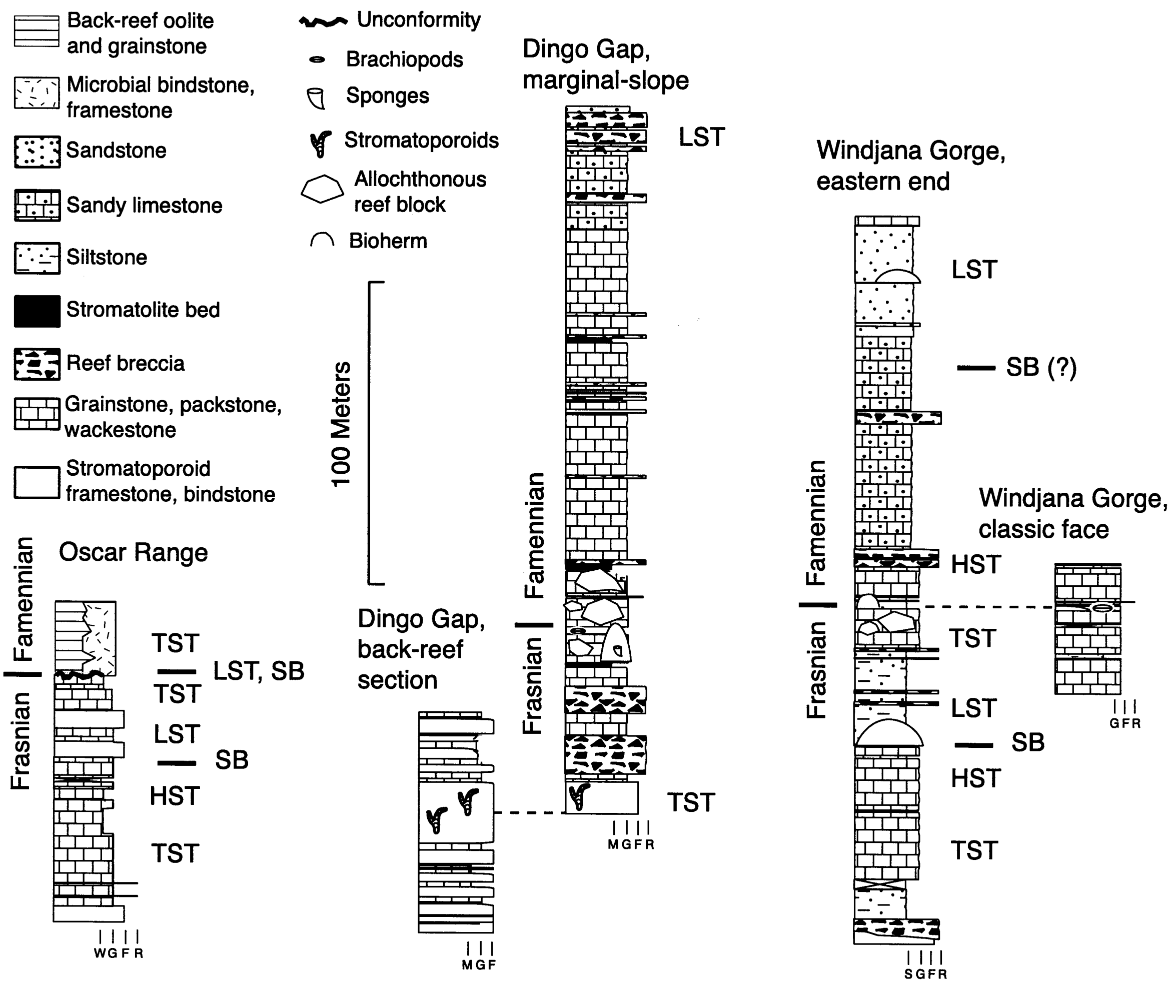

Fig. 5. Stratigraphic columns from Canning Basin and sea level interpretations based on facies relationships and facies composition (see Figs. 1–4 for locations of sections). TST–transgressive system tract, HST–highstand system tract, LST–lowstand system tract, R–reef breccia, F–framestone, G–packstone/grainstone, W–micrite/wackestones, S–siltstones, M–mudstones.

Stony Creek in the Canning Basin. At Dingo Gap, George et al. (1997) interpreted the transition from the carbonate-rich strata to the siliciclastic-rich strata in the Famennian as the result of a transition from highstand to lowstand conditions. Although siliciclastic sedimentation in a reef complex can be highly variable, the alternating carbonate and siliciclastic intervals at the eastern end of Windjana Gorge are probably the result of sea-level-driven reciprocal sedimentation (Fig. 5).

4.3. Results of carbon isotope geochemistry

The $\delta^{13}C$ curves for all stratigraphic sections have average baseline values of +1–+2‰ and positive excursions with $\delta^{13}C$ values ranging up to +6‰ (Fig. 6). The magnitude of the positive excursions varies among sections and may be a function of the material sampled with the most positive $\delta^{13}C$ values corresponding to brachiopods. The Dingo Gap and eastern Windjana Gorge sections have two broad, positive carbon isotopic excursions, one spanning 25 m across the Frasnian–Famennian boundary and a second be-

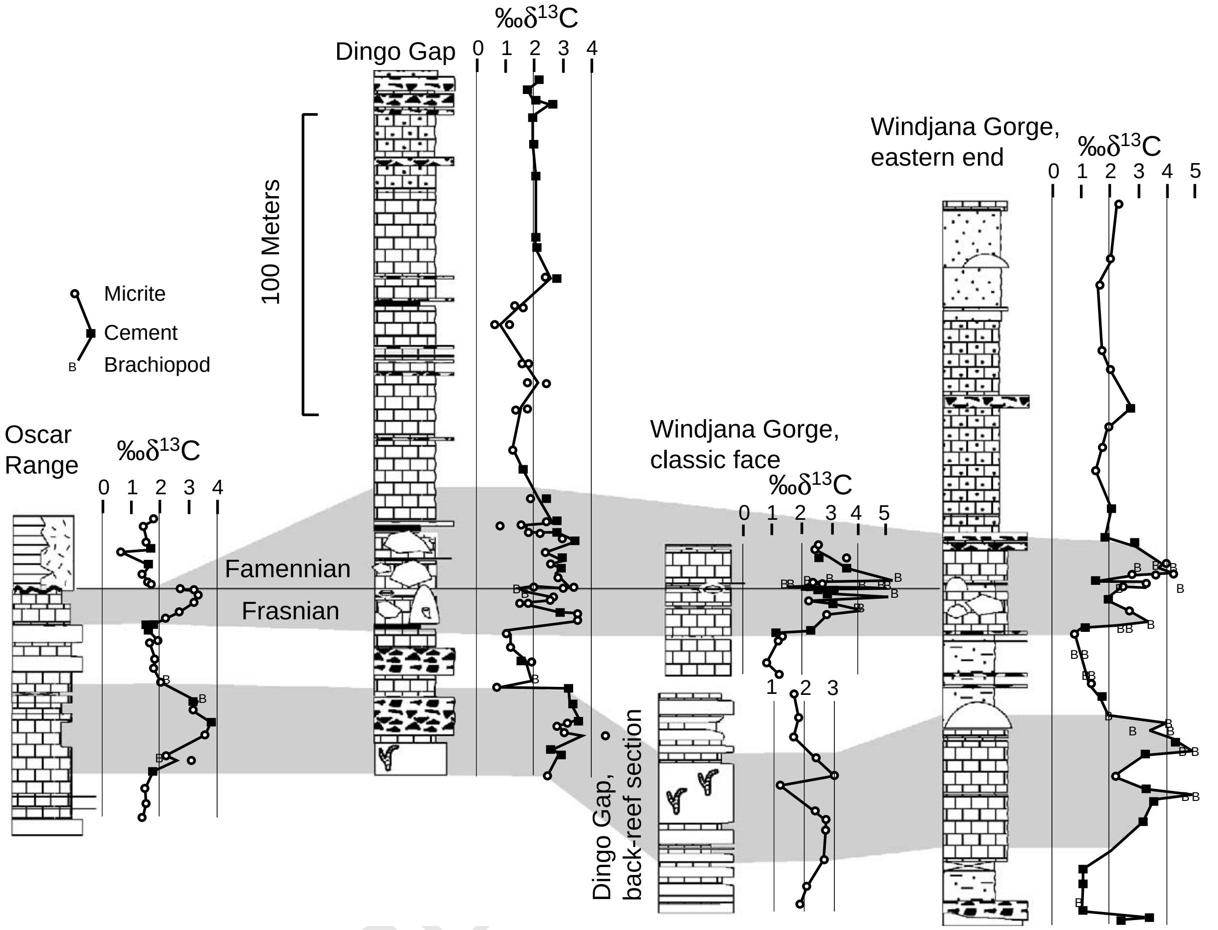

Fig. 6. Carbon isotopic correlation of Canning Basin sections. Where more than one data point exists for sampling horizon, carbon isotope curve is drawn through average of points. Gray field correlates positive carbon isotope excursions. See Fig. 5 for stratigraphic symbols and Figs. 1–4 for section locations.

tween 40 and 80 m below the Frasnian–Famennian boundary (Fig. 6). In the eastern Windjana Gorge section, the positive $\delta^{13}C$ excursions correspond to the more carbonate-rich intervals. Most of the Dingo Gap back-reef section consists of a positive excursion. The Oscar Range section contains two positive excursions, which lie 30–60 and 0–8 m below the Frasnian–Famennian boundary and occur in upper reef slope facies (Fig. 6). Unlike the other sections, the Oscar Range section does not show a positive $\delta^{13}C$ excursion in the earliest preserved Famennian strata (Fig. 6). Within the positive $\delta^{13}C$ excursions at Windjana Gorge and Dingo Gap, several sharp negative excursions drop to baseline values and are typically represented by one or two data points. One of these negative excursions is just below the Frasnian–Famennian boundary.

4.4. Diagenesis

The isotopic trends observed in the $\delta^{13}C$ curves are considered primary features based on petrography, luminescence, and $\delta^{18}O$ values (cf. Kerans et al., 1986; Hurley and Lohmann, 1989). Petrographically, neither the early marine cements nor the micrites show significant recrystallization. All analyzed brachiopods have well-preserved shell textures. The well-preserved petrographic textures of the micrites, early marine cements, and brachiopods suggest that major diagenetic alteration did not occur. Thin sections were screened for luminescence, which is caused by the diagenetic replacement of calcium in the calcite with manganese and iron. The samples chosen for stable isotope analyses were slightly luminescent to non-luminescent, which suggests little manganese substitution alteration. Carbon and oxygen isotopes in the stratigraphic sections lack typical trends attributed to diagenesis (cf. Hurley and Lohmann, 1989) (Fig. 7). The isotopic compositions of non-luminescent and slightly luminescent brachiopods, micrites, and cements overlap and lack correlations to manganese concentrations (data not shown). The lack of correlation of $\delta^{13}C$ values to sample type, luminescence, or $\delta^{18}O$ values suggests the $\delta^{13}C$ shifts were not due to diagenesis. In addition, the broad $\delta^{13}C$ trends are reproducible in all sections, regardless of the lithologic differences between the sections. Thus, the broad $\delta^{13}C$ trends are almost certainly original.

4.5. Carbon isotope stratigraphy

The broad trends in the $\delta^{13}C$ curves are interpreted as global and can be used for correlation of strata in the Canning Basin. The Canning Basin had open circulation with seawater (Carpenter et al., 1991), and all sections measured were in the mixed layer of the water column and should not show isotopic anomalies due to basinal stratification. Global correlations based on the available biostratigraphic data from Dingo Gap, Europe, and Canada consistently show two positive $\delta^{13}C$ excursions in the upper *rhenana* to *linguiformis* biozones confirming that the $\delta^{13}C$ excursions are global signatures (Fig. 8) (Joachimski and Buggisch, 1993; Wang et al., 1996). Thus, the upper Frasnian to lower Famennian strata with the pos-

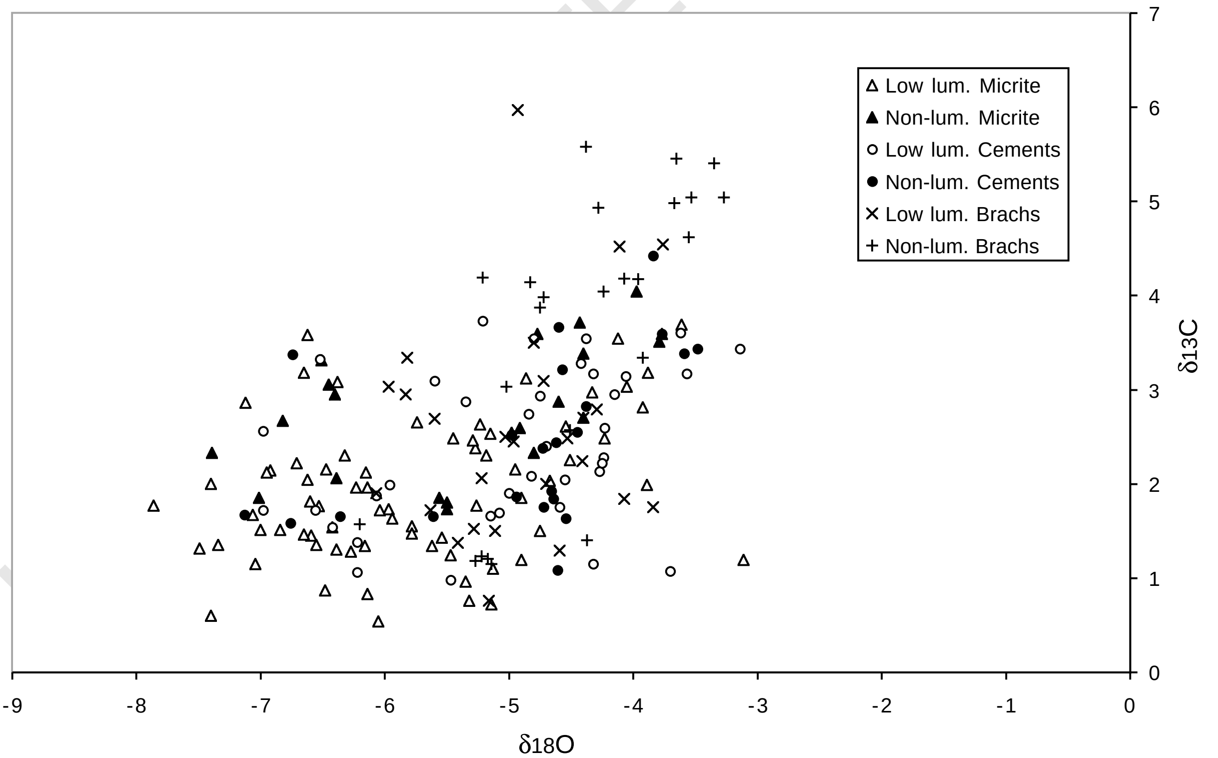

Fig. 7. Carbon and oxygen isotopic values of samples used for $\delta^{13}C$ correlations.

itive carbon isotope excursion were deposited at the same time.

The lower positive $\delta^{13}C$ excursion correlates transgressive intervals at Dingo Gap, Oscar Range, and Windjana Gorge (Figs. 5 and 6). The back-stepping reef platform from the Oscar Range and platform B in the Napier Range are below the lower positive $\delta^{13}C$ excursions, suggesting that these back-stepping events were roughly synchronous in the Oscar and Napier Ranges (Fig. 6). The positive $\delta^{13}C$ excursion corresponds to a deepening depositional environment in the Oscar Range, an aggrading and back-stepping reef platform at Dingo Gap, and a carbonate-rich interval in the marginal slope strata at Windjana Gorge. Based on sedimentary indicators of sea level change, a transgression occurred at the three locations in the Canning Basin during the lower positive $\delta^{13}C$ excursion.

Between the upper and lower positive $\delta^{13}C$ excursions, the sedimentary indicators of sea level at the Oscar Range and Windjana Gorge suggest a drop in sea level. During this interval, the advancing reef margin in the Oscar Range corresponds to the late Frasnian siliciclastic interval at Windjana Gorge. The reef breccias at Dingo Gap are somewhat ambiguous as to whether they formed during a transgression or regression (George et al., 1997). However, by correlating the low $\delta^{13}C$ interval at Dingo Gap to the Oscar Range section, the breccias can be interpreted as initiating during a highstand and continuing into a lowstand (Fig. 6).

The upper positive carbon isotopic excursion correlates transgressive, upper marginal slope strata in the Oscar Range with carbonate-rich intervals in both Windjana Gorge and Dingo Gap. George et al. (1997) also interpreted parts of this interval as transgressive at Dingo Gap. Based on $\delta^{13}C$ correlation with the Oscar Range and Dingo Gap, the origin of the reciprocal carbonate–siliciclastic sedimentation at Windjana Gorge can be confirmed as sea-level-driven. Stratigraphically above the upper positive $\delta^{13}C$ excursion, the strata at both Windjana Gorge and Dingo Gap grade from carbonates to siliciclastics, suggesting a drop in sea level at both locations, based on models of reciprocal sedimentation. For much of the Famennian strata, the carbon isotopic curves are consistently at baseline values of around 2‰, which correspond to the lack of transgressive intervals in the lower Famennian.

At Dingo Gap and Windjana Gorge, sharp decreases in $\delta^{13}C$ punctuate the broad positive $\delta^{13}C$ excursions and may represent either remixing of older sediment or short-term fluctuations in the carbon cycle. Mass wasting of the reefs created reef breccia beds and allochthonous reef blocks in the marginal slope and may have mixed carbonate material with varying original $\delta^{13}C$ values. Brief changes in ocean chemistry and ocean circulation also can produce sharp negative $\delta^{13}C$ excursions (Kump, 1991; Spero and Lea, 2002), which may be superimposed on the broad positive $\delta^{13}C$ excursion of the Late Devonian. Also, variable $\delta^{13}C$ values within a stratigraphic horizon may be explained by changes in the $\delta^{13}C$ value of seawater during the intervals between micrite formation, brachiopod growth, and cementation of the voids. However, the identification of a sharp negative $\delta^{13}C$ excursion as mixing of sediment or a short-term change in ocean chemistry can be difficult. The negative $\delta^{13}C$ excursion just below the Frasnian–Famennian boundary at Windjana Gorge may represent a short-term change in ocean chemistry (Fig. 6), because low $\delta^{13}C$ brachiopods at the Frasnian–Famennian boundary have both valves intact and do not appear abraded, suggesting very little syndepositional transport.

5. Discussion

In addition to the sequence stratigraphy and biostratigraphy, carbon isotope stratigraphy provides a way of correlating time-equivalent upper Frasnian to lower Famennian strata. This correlation can extend sequence stratigraphic interpretations and help differentiate eustatic versus tectonic subsidence. We interpret changes in sea level in the Canning Basin as eustatic in origin, based on correlations of $\delta^{13}C$ fluctuations (Fig. 8). In the Canning Basin and Europe, transgressive intervals correspond to positive $\delta^{13}C$ excursions. In Europe, the positive $\delta^{13}C$ excursions are found within the transgressive Kellwasser horizons (Joachimski and Buggisch, 1993). The late Frasnian to early Famennian transgressions occurred at the same time in Europe and Australia and are almost certainly eustatic in origin. Although the Canning Basin was tectonically active during Devonian time, eustatic fluctuations were superimposed on tectonic subsidence and were largely responsible for changes on facies composition and distribution in the upper Frasnian and lower Famennian strata.

The correlations within the Canning Basin refine the sequence stratigraphic framework. Our transgressive interval across the Frasnian–Famennian boundary agrees with Canning Basin subsurface data (Kennard et al. (1992); Southgate et al., 1993) and some global sea level interpretations (Hallam and Wignall, 1999). This transgression and corresponding positive $\delta^{13}C$ excursion are part of the 'Frasnian–Famennian' sequence of Kennard et al. (1992) (Fig. 9). The Frasnian lowstand reef at the Oscar Range probably correlates with the lowstand reef tongue at the 'classic face' of Windjana Gorge (Whittam et al., 1994). The lower positive $\delta^{13}C$ excursion and transgressive interval correspond to Southgate et al.'s (1993)

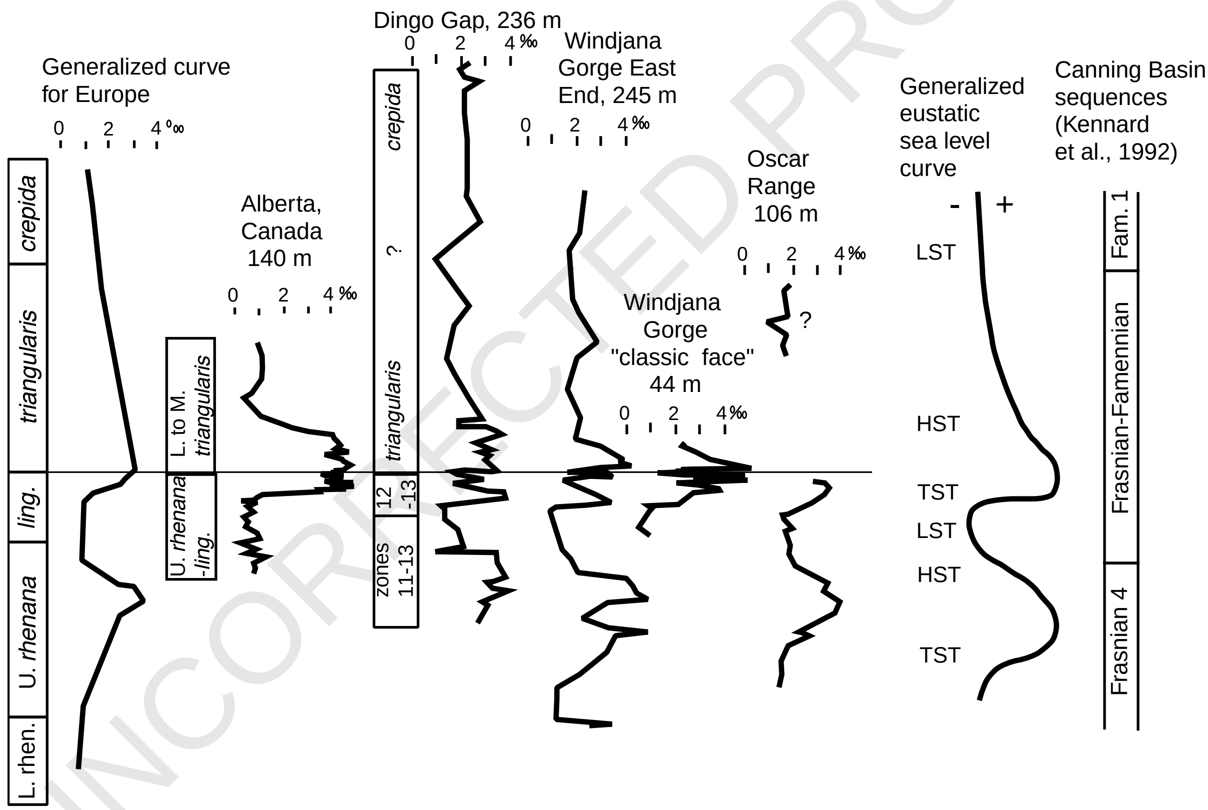

Fig. 8. Late Devonian $\delta^{13}C$ curves from Canning Basin compared to generalized carbon isotope curve from Europe (Joachimski and Buggisch, 1993) and carbon isotope curve from Canada (Wang et al., 1996). The $\delta^{13}C$ curve from Europe is plotted against time. $\delta^{13}C$ curves from Australia and Canada are plotted against thickness and adjusted so conodont dates correlate with the European section. In conodont classification schemes, Frasnian biozone 13 is in upper *rhenana* to *linguiformis* biozones, and biozone 12 is in lower to upper *rhenana* biozones (Klapper and Becker, 1998). Gap in Oscar Range curve is due to unconformity, and placement of upper segment of this curve is uncertain. The generalized eustatic sea level curve is interpreted from Canning Basin and European sections (Joachimski and Buggisch, 1993) and agrees with Hallam and Wignall's (1999) interpretation. This curve does not include possible short-term fluctuations in sea level, such as the one which may have occurred at the Frasnian–Famennian boundary.

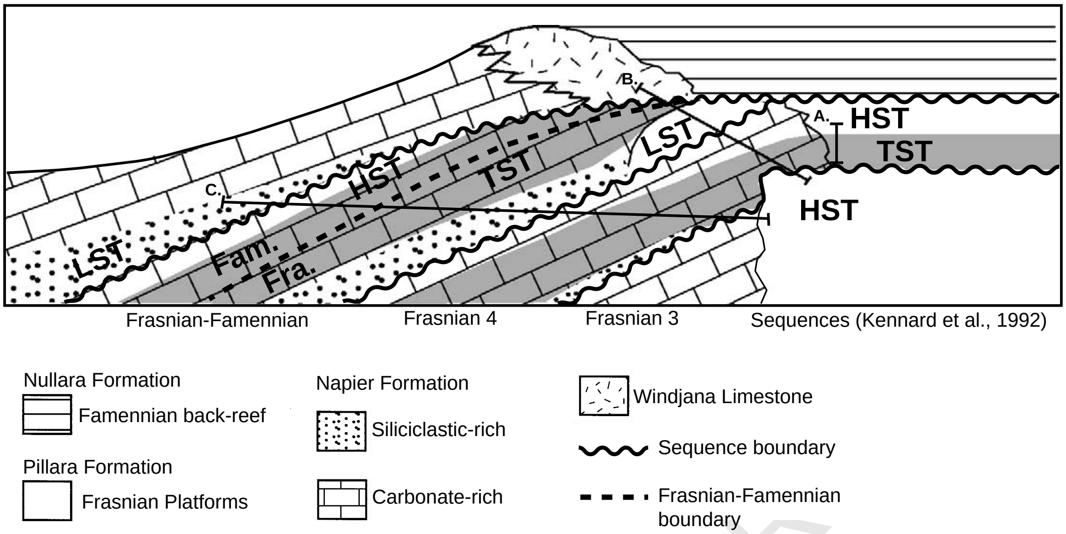

Fig. 9. Sequence stratigraphic interpretation based on Dingo Gap, Oscar Range, and Windjana Gorge stratigraphy and carbon isotopic data. Section A is back-reef of Dingo Gap, section B is from Oscar Range, and section C is Windjana Gorge. Shaded areas correspond to positive carbon isotope excursions. Sequence stratigraphic interpretation agrees with Kennard et al.'s (1992) and Southgate et al.'s (1993) interpretations.

'Frasnian four' sequence (Fig. 9). Further correlations of these sequences within the Canning Basin and globally can be aided by additional use of carbon isotope stratigraphy.

The Canning Basin shows some evidence for a drop in sea level at the Frasnian–Famennian boundary. At Windjana Gorge, a thin, 2-m, siltstone interval at the Frasnian–Famennian boundary may represent a drop in sea level. The siltstone and possible stromatolites at this interval may have been deposited as a function of sea-level-driven reciprocal sedimentation. This interval also may correspond to a stromatolite horizon at Dingo Gap, which George et al. (1997) interpret as a drop in sea level at the Frasnian–Famennian boundary. The negative $\delta^{13}C$ excursion in the brachiopods just below the Frasnian–Famennian boundary in the 'classic face' of Windjana Gorge may be recording an isotopic shift associated with a short-term drop in sea level.

However, the drop in sea level at the Frasnian–Famennian boundary is interpreted as a short-term event superimposed on a broad transgression. Upper marginal slope facies at Windjana Gorge were not exposed at the Frasnian–Famennian boundary suggesting that the drop in sea level was substantially less than the 150-m drop reported at the Frasnian–Famennian boundary in Canada (Mountjoy and Becker, 1996) and other locations around the world (Hallam and Wignall, 1999). At the Oscar Range, an erosional surface is present at the Frasnian–Famennian boundary (Playford et al., 1989). However, the upper positive $\delta^{13}C$ excursion in the Oscar Range lies below the unconformity and is interpreted as entirely Frasnian based on the abundance of stromatoporoid fragments (Fig. 6). Since none of the positive $\delta^{13}C$ excursion is Famennian, the lower Famennian, transgressive strata that contain the $\delta^{13}C$ shift elsewhere in the basin must have been eroded away from the Oscar Range reef complex during a later drop in sea level during early Famennian time (Fig. 9). Thus, the sedimentological evidence in the Canning Basin suggests that the drop in sea level at the Frasnian–Famennian boundary was a short-term event superimposed on a third-order transgressive to highstand interval and was masked in shallow-water depositional environments by a greater drop in sea level which occurred during early Famennian time.

The correspondence of $\delta^{13}C$ variations to inferred sea level changes suggests a dependence of the Late Devonian carbon cycle on changes in ocean circulation and possibly climate. High $\delta^{13}C$ values may reflect times of high organic carbon burial in continental and oceanic sediments (Joachimski and Buggisch, 1993; Wang et al., 1996; Joachimski et al., 2002). Density-stratified epeiric seas and other sedimentary basins produced black shales at several locations globally during Late Devonian time, especially during transgressions (Witzke and Heckel, 1988; Joachimski et al., 2001). By removing isotopically light organic carbon from the oceans, the dissolved inorganic carbon become isotopically heavier and become incorporated into calcite cements (Kump and Arthur, 1999; Joachimski et al., 2001). Alternatively by removing carbon dioxide from the atmosphere and oceans during burial of organic carbon, Late Devonian sea surface temperature probably decreased and pH of the oceans increased, possibly resulting in an increase in seawater $\delta^{13}C$ values due to inorganic fractionation (Lynch-Stieglitz et al., 1995; Spero et al., 1997). During lowstands, destabilization or lowering of the pycnocline of these basins may have occurred due to changes in circulation or climate (Wignall, 1994; Joachimski et al., 2001). This may have resulted in the release and oxidation of isotopically light sedimentary organic carbon and methane clathrates, causing seawater $\delta^{13}C$ values to return to baseline levels (Buggisch, 1991; Haq, 1998).

6. Conclusion

In conjunction with biostratigraphy and sequence stratigraphy, carbon isotope stratigraphy provides a powerful tool for correlating upper Frasnian and lower Famennian strata and is especially useful in shallow-water reef environments, where biostratigraphic data are typically lacking. Fluctuations in global carbon isotopic values are a function of a sea-level-driven carbon cycle, and positive $\delta^{13}C$ excursions correspond to eustatic highs. At Windjana Gorge, reciprocal carbonate–siliciclastic sedimentation was driven by eustatic sea level changes, and based on positive $\delta^{13}C$ excursions, carbonate-rich intervals at Windjana Gorge correlate to other transgressive interval in the Canning Basin and Europe. Carbon isotope stratigraphy also reveals the correlation between lowstand reefs in the Oscar Range with siliciclastic deposition at Windjana Gorge. A minor drop in sea level probably occurred at the Frasnian–Famennian boundary, which was eroded from shallow-water reef environments by a greater drop in sea level during early Famennian time. Based on biostratigraphy, sequence stratigraphy, and carbon isotope stratigraphy, correlations in the Canning Basin help develop a sequence stratigraphic model, from which other upper Frasnian–lower Famennian sections can be compared.

7. Uncited references

Racki, 1999; Spero, 1992

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