INTRODUCTION

We are gratified by the interest that our publication has generated and thank Machel et al. (2002, this issue) for their discussion. However, we do not agree with their assessment of the part of our paper dealing with a mechanism for the formation of replacement dolomite in the Frasnian second-order sequence. We assert that, considering all the data, the most logical explanation for the mechanism of formation for these dolomites is by seepage refluxion with fluids originating at or near the top of the Frasnian sequence.

One of the hallmarks of a good dolomitization model is its ability to explain and predict dolomite distribution in space and time. This makes it useful to researchers and to geologists exploring for dolomite reservoirs. The proposed mechanism accomplishes this. We have taken a substantially different approach to understand the mechanism of dolomite formation than that taken by H.G. Machel and his colleagues.

Our conclusions about dolomite timing and dolomitizing fluid are based primarily on regional stratigraphic analysis; their conclusions have relied somewhat more heavily on isotopic analyses. We do not apologize for taking a more straightforward, observational approach. Rather, we regard our work as an important contribution to the understanding of these rocks, because it presents a model based on knowledge of the regional stratigraphic distribution of the replacement dolomite. Many dolomitization studies in the Western Canada Sedimentary Basin (WCSB) have been investigations of relatively small areas, have not incorporated all of the relevant stratigraphy, or have lacked the scope to tackle the regional issues. The intent of our paper was to present a regional stratigraphic framework and not to criticize previous work. Rather, we wished to propose an alternative mechanism tied closely to a stratigraphic model.

Amthor et al. (1994) also recognize the importance of a predictive model in their assertion that, to be dolomitized, the Leduc Formation reef target must be connected to a regional conduit system. However, the proposed regional conduit system — the Cooking Lake and lower Leduc formations — does not explain the distribution of the Leduc Formation dolomite at Sturgeon Lake or Fenn-Big Valley (their proposed regional fluid conduit is limestone), among others. As discussed herein, the model of Machel and Anderson (1989) for the Nisku Formation in west Pembina is also problematic, as is the model of Duggan et al. (2001) for the Swan Hills Formation at Simonette. As a result, we have been sceptical of their approach, which led us to our own study of Frasnian dolomites as part of our exploration focused stratigraphic work.

It is worth emphasizing the level of confidence that can be placed in various types of data. In geochemical analysis, uncertainty arises from one or more of the following: sampling error, measurement error and geologically- or chemically-based error. Geologically-based error results from, among other things, uncertainty in the chemical composition of the initial rock and fluids, uncertainty and assumptions about how the various chemical components fractionate, and whether and how much subsequent neomorphism has reset these components. The first two errors can be controlled through careful laboratory technique and we are not suggesting that this has not been undertaken. However uncertainty arising from the geologically- and chemically-based error is extremely difficult to assess. Hydrologic models suffer from uncertainty in the regional basin hydrology, distribution of porosity and permeability in the aquifers, original water chemistry, etc. Recognition of dolomite and limestone in outcrops and subsurface datasets, consisting of petrophysical well logs, cores and drill cuttings, is relatively unambiguous but stratigraphic analysis does involve interpretation and interpolation between the well and outcrop control points.
Machel et al. (2002, this issue) state, and we fully agree, that it is important to work cautiously and critically, to gather many lines of evidence, to consider all available data, and to present well supported conclusions. They also suggest that we did not follow these guidelines. In this reply we will show that we have carefully considered the data, both published and our own, and that the balance of the evidence supports our conclusions. As well, Machel et al. (2002, this issue) accuse us of ignoring much of the previous work that they have undertaken. This is not true. We have read the work of their scientific team and attended many of their oral presentations over the past 15 or so years. However, as exploration geologists, we find their conclusions regarding the replacement dolomites unsatisfactory in two important areas. First, their work has not adequately explained the present day dolomite distribution within the Frasnian succession. Second, and perhaps most important, their work did not allow us to predict, prior to drilling, the presence of dolomite within these rocks which, because of the resultant reservoir quality, was one of our primary exploration goals.

This reply contains further examples of dangerous pitfalls in the methodology and analysis of age and formation mechanism of replacement dolomites, in which temperature determined from oxygen isotopes is a primary tool. These pitfalls and the consequent incorrect conclusions drawn from the data are compounded by insufficient analysis of a basin’s stratigraphy.

First, we discuss the different approaches used by us (Potma et al., 2001) and by Machel et al. (2002, this issue). Then, we have divided their concerns and our discussion into six critical areas.

**OUR APPROACH**

As outlined in Potma et al. (2001), our work uses basic science. When we collected what we regard as pertinent data, we assessed the distribution of Frasnian replacement dolomite and limestone in the area of the basin from Twp. 25 to 80 Rge. 10 W4 to Rge. 15 W6 both areally and temporally. Data sets included a corporate database of drill cuttings lithology (Canstrat), cores, and hundreds of well logs. The selection of modern density-neutron and photoelectric effect logs, and placement of many of these onto local and regional cross-sections, facilitated rapid identification and mapping of dolomite and limestone. In addition, we mapped the extent of potential vertical permeability barriers, such as the Ireton Formation shales. In addition to our subsurface work, outcrop description of the unconformities revealed the association of evaporative conditions with dolomite. At Cripple Creek, for example, we observed the presence of hopper crystal casts (after halite) in Calmar and Graminia formation siltstones.

These data were incorporated into a stratigraphic framework of the basin (Potma et al., 2001, Fig. 2). The framework provided knowledge about lithofacies and the resultant porosity and permeability distribution within aquifers, and an understanding of the aquitards. The significance of the sequence boundaries, their hierarchy and their potential as brine generators was also evaluated.

Areas where there was the potential for evaporation of seawater to gypsum saturation within and outside the Frasnian second-order sequence were noted and mapped. There is clear evidence for widespread evaporative conditions in the Nisku Formation and the Blueridge Member (Graminia Formation), including numerous small sub-basins with bedded anhydrites (Switzer et al., 1994). Review of regional Devonian maps and cross-sections of western Canada (e.g. Mossop and Shetson, 1994) reveal the repeated association of evaporites and dolomite, most notably in the Eifelian to lower Givetian (Elk Point Group), but also through the Frasnian on the southern Alberta Shelf. The shelf represents an area, and dolomite volume, much greater than the remaining isolated reefs to the northwest in our area of interest.

Integration of these data led us to recognize the importance of the uppermost Frasnian third-order sequences as a likely time for the generation of the vast quantity of magnesium-bearing fluids required to dolomitize the underlying strata. That knowledge, together with the observed dolomite distribution patterns, led to the development of our model. Petrographic and isotopic data were consistent with this model.

The Chevron Exploration Staff (1979) proposed the idea of seepage refluxion from the Blueridge Member for the West Pembina area. Potma and Wong (1995) were the first to propose a regional seepage reflux model for the Frasnian. Shields and Brady (1996) made compelling mass balance and stratigraphic arguments for dolomitization of these rocks by seepage refluxion. Al-Awar (1996) concluded that Nisku dolomites in the Joffre area were formed by seepage of time-equivalent brines. Wendte et al. (1998) proposed a variant of the reflux model; thermally driven Winterburn Group brines causing dolomitization of the Winterburn, Woodbend and Beaverhill Lake groups in the Wild River area of the Alberta deep basin.

**APPROACH OF H.G. MACHEL, E.W. MOUNTJOY AND THEIR STUDENTS**

Considerable work has been done by H. G. Machel and his colleagues on the origin of Devonian dolomites in the WCSB. They claim it is comprehensive, involving 15 years and many scientists. However, in their discussion, Machel et al. (2002, this issue) summarize the origin of replacement dolomitization as “accomplished by seawater that was chemically modified to a minor, yet significant, degree, and that was driven in some hitherto unknown manner through the Devonian strata when they were being buried to depths of about 500 to 1500 m.” This conclusion, following years of work, is less than satisfying.

We believe this is because they did not try to understand the regional stratigraphy that provides information on the logical times of dolomite formation or the “plumbing system” for fluid movement. This is a basic requirement of a model that claims to have regional significance. Numerous papers, for example Mountjoy et al. (1999), lack detailed regional maps.
or cross-sections, and provide little discussion of the regional, three-dimensional distribution of dolomite. This is especially true for the Nisku and Graminia formations. We will give several examples in which we believe that this incomplete investigation of the stratigraphy has led to incorrect conclusions. The lack of a suitable framework has not allowed them to put their more detailed work into a regional predictive context.

Voluminous work by Machel, his colleagues and their students, on the petrology and geochemistry of the dolomites, has been done using a wide array of equipment and techniques. However, interpretations of some of these data are equivocal, because the conclusions are based on some dubious, and probably incorrect, imbedded assumptions. Among these are assumptions about original fluid chemistry, and the assumption that no significant neomorphism of the original replacement dolomite has occurred (Amthor et al., 1993, p. 176-177). We will present additional data supporting our conclusions presented in Potma et al. (2001); namely, that significant resetting of oxygen isotopes likely occurred. The assumption that the initial dolomite formation temperature can be determined through a chemical analysis has not been proven for in these strata.

Similarly, they conducted hydrogeological modeling (Jones and Rostron, 2000), but this was also based on an incomplete investigation of the stratigraphy and the possible sources of potential dolomitizing fluids. Conclusions drawn from these models are, therefore, not relevant to the Frasnian of this basin.

We will now discuss some of the data required to build an understanding of potential dolomitizing mechanisms. We will show that the dolomite distribution pattern, potential dolomitizing fluids, petrography, geochemistry and the timing of dolomitization are all consistent with our proposed seepage mechanism.

**Spatial distribution of dolomite**

We presented a summary of the regional distribution of dolomite in Potma et al. (2001). The pattern is one of extensive, near complete, dolomitization of the upper part of the second-order sequence, whereas older, higher frequency sequences were dolomitized where porous and permeable flow paths existed between them and the younger third-order sequences. We believe this pattern is the most compelling evidence for seepage refluxion, from the top of the Winterburn Group, as the dominant mechanism for the formation of the replacement dolomite.

Machel et al. (2002, this issue) have not sufficiently investigated these stratigraphic relationships. A recent example is from the Simonette area in Duggan et al. (2001). Their Figure 15 places shale at the top of the Winterburn Group in their wells “a” through “e” despite the fact that these rocks actually consist of up to 60 m of dolomite sometimes overlain by 6 m of anhydrite. This can be seen in well logs over the interval between 3283 m and 3347 m in 13(16)-9-64-26W5, their well “d’. A few miles to the west of their well “a”, in 2-30-63-2W6, the Winterburn Group dolomites and Leduc Formation dolomites are in continuity. The overlying Wabamun Group is almost entirely limestone. They overlook such stratigraphic data supporting Frasnian-age brine generation. Instead, they rely more heavily on temperatures derived from isotope data, and propose replacement dolomitization in the Swan Hills Formation by “possible significant flow” down a fault from the Mississippian, even though they present no hard evidence supporting the presence of such a fault. We assert that the bulk of the evidence supports a mechanism of gravity flow of brines from the Graminia Formation/Blueridge Member to the Swan Hills via the Leduc Formation reef. The isotopic pattern can be explained within this mechanism as resulting from late burial, higher temperature neomorphism, and cementation with perhaps an overprinting by late stage hydrothermal fluids.

In their study of Nisku Formation dolomitization along the West Pembina trend, Machel and Anderson (1989) do not describe the overlying Blueridge Member. This was omitted even though the Blueridge Member contains more dolomite volumetrically than the underlying Zeta Lake Member reefs, the Bigoray and the Lobstick members combined. The Blueridge Member contains bedded anhydrites, indicating a strong potential for the creation of magnesium-rich brines. An example is the interval between 2323 m and 2358 m in the Esso Bigoray 6-12-52-9W5 well in the Bigoray C pool (misnamed 6-12-52-8 in their paper). By overlooking these data, Machel and Anderson (op. cit.) discount density driven dolomitization, though they consider it a theoretical possibility. Furthermore, despite this stratigraphic evidence, they state incorrectly that “density driven convection is not a viable alternative for Nisku matrix dolomites because brines dense enough for deep penetration were never formed at the surface after Nisku deposition” (op. cit., p. 909).

Machel and Anderson (1989) use upward increases in Sr concentrations as evidence for upward fluid flow. They do not consider, or test the possibility, that this was a downward trend with Sr concentration decreasing away from the Graminia silts that overlay their sampled cores. This is a commonly observed trend in interbedded carbonates and siliciclastics (e.g. Allan and Wiggins, 1993). Al-Awar (1996), for example, noted that Sr concentration increased towards the siliciclastic layers in the Nisku Formation at Joffre Field.

In discussing our work, Machel et al. (2002, this issue) refer to Rosevear and Hanlan as examples where the overall extent of replacement dolomitization increases downward. Reference to the stratigraphy indicates that this statement is false. The well logs at Rosevear show that the uppermost Winterburn sequence (Blueridge Member, Graminia Formation) is dolomite and anhydrite. An example is the 103 m interval from 2683 m to 2786 m in the 1-27-54-15W5 well. This well has 18 metres of Swan Hills Formation dolomite (3202 m to 3220 m). Similarly, the 8-11-54-15W5 well contains 75 m of dolomite in the uppermost Winterburn. Descriptions of the Rosevear Field by Kaufman (1988) indicate a narrow marine embayment or channel into the Swan Hills Platform. Replacement dolomite consists of two narrow geobodies that resulted from dolomitization of margin facies on either side of the channel. These geobodies occur in the middle third of the Swan Hills Formation. The underlying lower platform (BHL1 sequence) and the overlying
upper Swan Hills Formation (BHL3 sequence) do not have this facies differentiation and are predominantly limestone. Pool designations by the Alberta Energy and Utilities Board, based on reservoir pressures and extracted gas volumes, are consistent with this description. The Beaverhill Lake A pool geobody is about 14 km long, 1.5 km wide and 40 m thick. The Beaverhill Lake B pool geobody is about 10 km long, 1.5 km wide and 40 m thick. Total volume of Swan Hills dolomite is about 0.8 km$^3$ and 0.6 km$^3$, respectively. The Graminia Member dolomite is regional and so covers a much larger area. However, taking only the 9.6 km by 9.6 km area (township) directly overlying the Rosewarne Field, and multiplying by an average thickness of 90 metres, results in 8.29 km$^3$ of dolomite. Thus, the assertion by Machel et al. (2002, this issue) of increasing amounts of Frasnian dolomite with depth in these areas is incorrect, because there is about 5.7 times more dolomite stratigraphically higher in the section. A similar argument applies at Hanlan.

The well control is not sufficient to map the northwestern extension of the channel. It is plausible that a replacement dolomite conduit extends within the Swan Hill Formation for 10 km further and that this is plumbed to the Winterburn dolomites via the Windfall Leduc Formation reef complex.

Another example is Figure 1 in Mountjoy et al. (1999). As we have shown in our Figure 28b (Potma et al., 2001) and Switzer et al. (1994) in their Figure 12.11, the Sturgeon Lake Leduc Formation reef is dolomite, not limestone as they have shown. In our paper we discussed the importance of this area as an isolated dolomitized reef on a local limestone platform with no potential for dolomitizing fluids to access it except from above. As such, it cannot be dolomitized via the “regional conduit” proposed by Amthor et al. (1994).

In the above examples H.G. Machel, E.W. Mountjoy and their co-workers have avoided the comprehensive stratigraphic work necessary to provide an accurate regional synthesis of temporal or spatial dolomite distribution. Their maps and figures do not accurately reflect the dolomite distribution and their conclusions do not incorporate the implications.

Machel et al. (2002, this issue) state, in their discussion, that if our model is correct, there should not be any replacement dolomite older than the age of the Calmar Formation or any younger than the Winterburn 3. Then they describe two examples where this occurs. This argument does not withstand scrutiny.

Examination of our Figure 28d (Potma et al., 2001) shows that we do, in fact, suggest the possibility of seepage reflux dolomite on other third-order sequence boundaries. There is also the potential for more local replacement dolomites where local paleogeographic conditions allowed it. These settings would include the Grosmont dolomites of Theriault and Hutcheon (1987). In the course of our work (K. Potma and J. Kaufman), we also noted potential local reflux dolomites in the Beaverhill Lake in eastern Alberta. However, our basin-wide mapping leads us to conclude that the volume of these very early dolomites is small relative to the later Frasnian replacement dolomites, especially in our study area. As mentioned previously, large volumes of dolomite, anhydrite and associated halite occur in southern and eastern Alberta.

Machel et al. (2002, this issue) correctly point out that there are places, such as Pine Creek and the Peace River Arch, where younger Famennian age (Wabamun Group) dolomites are present. These dolomites, and the fact that they are texturally similar to Frasnian dolomites, cannot be used to discredit our work. Based on the stratigraphic association of salts, anhydrites and dolomites within the Wabamun Group we would conclude that there was likely a viable reflux system operating during Wabamun deposition as suggested by Shields and Brady (1996). Machel et al. (2002, this issue) assume that the intent of the paper was to explain every occurrence of Devonian dolomite in the WCSB. We did not state this. Although we think our model can be applied to the bulk of the Frasnian replacement dolomites, there are clearly other dolomites in the basin. The Wabamun dolomite at Pine Creek (Green, 1999) would, of course, postdate our replacement dolomite. Irrespective of the “similar texture”, the stratigraphic distribution of the Pine Creek and similar dolomites shows that they formed in a different dolomitizing environment. Our work in this area suggests that these facies selective, tabular and linear trend dolomites result from fluids coming from below via post-Famennian faults, some associated with brittle failure resulting from drape due to compaction of underlying Frasnian shales. The Wabamun dolomites on the Peace River Arch are also entirely different. The Peace River Arch is a place that was undergoing wrench and extension tectonism beginning in the Early Mississippian. The presence of blocks of overlying Carboniferous strata in the linear chert and dolomite trends clearly show that these are hydrothermal geobodies on a tectonically collapsing arch (Packard et al., 2001). The presence of these dolomites does nothing to discredit our work within the Frasnian.

In summary, despite the stratigraphic evidence, Machel et al. (2002, this issue) have not tried to understand the potential of the upper part of the Winterburn Group as a brine generator. Their failure to undertake such a regional synthesis has prevented them from putting their more detailed geochemical work into a reasonable conceptual framework. However, as we stated in our paper (Potma et al., 2001), the stratigraphic distribution of dolomite within the study area is both consistent with a model of dolomitization by seepage reflux and compelling evidence for it.

**Fluids available for dolomitization**

In our view, as well as those of Shields and Brady (1996) and Wendte et al. (1998), mass balance arguments dictate that brines formed from Devonian seawater and flowing in an open system are the only fluids capable of forming the large volume of Frasnian replacement dolomite observed in the rock record. Severe mass-balance problems resulting from the use of shale waters for dolomitization, for example the funneling of compaction-driven connate water (Mountjoy et al., 1999), have been discussed at length in Kaufman (1994) and by Shields and Brady (1996) and are not repeated here.

In their efforts to find a larger volume shale to serve as a magnesium source, Mountjoy et al. (1999) propose tectonically
expelled fluids resulting from Mississippian Antler orogenesis. This model is problematic. First, it removes the discussion (conveniently and unnecessarily) outside the Alberta basin, to an area where the Devonian and Mississippian strata are little known due to significant Laramide tectonism and subsequent erosion. Second, the problems with shale-sourced magnesium are not surmounted. There is still insufficient magnesium. Using the mass balance calculations of Shields and Brady (1996), the tectonically compacting shale volume would have to be almost 100 times larger than the shale volume of the Alberta basin. Furthermore, all of its magnesium would have to have been directed into the Alberta basin, despite the fact that the primary flow of fluids in compacting shales is typically upward, not lateral, unless there are highly permeable beds present (Kaufman, 1994). Third, the tectonic fluid model is not supported by lithological data. The amount of dolomite decreases toward the west in the Fammennian and Mississippian strata. If westerly-derived tectonically expelled fluids were resulting in replacement dolomitization, the opposite should occur. In addition, except for the Peace River Arch, which undergoes collapse in the late Mississippian (Richards, 1994), there is no evidence for large scale mountain-building along the immediate west side of the Alberta basin in Fammennian through Mississippian time that could drive such a mechanism. Work by Root (2001) suggests that the western “tectonic” regime could largely involve island arcs within a proto-Pacific ocean.

Machel et al. (2002, this issue) refer to the work of Root (2001) as evidence of an upper Devonian Antler Orogeny. However, Root primarily describes middle Devonian tectonism in the areas to the west of our study area. The Starbird Formation, according to Root (2001), is Frasnian. He states that “no deformation can be conclusively documented in the Delphine Creek area during Starbird Formation deposition” and “strata younger than the Starbird Formation are not preserved” (op. cit., p. 22). So, in his study “there are no stratigraphic data that could indicate whether additional deformational episodes occurred later in the Devonian or Mississippian”. Machel et al. (2002, this issue) speculate about, but do not provide stratigraphic evidence for, a mechanism that would provide tectonically expelled fluids to the Alberta basin.

In the West Pembina area Machel and Anderson (1989) propose thermal convection cells operating within the Ireton and Waterways formation shales and tight limestones as the dolomitizing mechanism. Recognizing the limitations of the shales as a magnesium source, they increase the amount of magnesium available to the thermal circulation cells by having the cells “penetrate the underlying Middle Devonian evaporite section” (op. cit., p. 908). They did this despite the fact that there are no evaporites present in the Middle Devonian in the West Pembina area. The middle Devonian is at or near its western depositional limit against the Cambrian rocks of the West Alberta Ridge and consists of 0 to 140 metres of interbedded shales and minor siliciclastics. Examples are the interval from 11,300ft. (3444 m) to 11,484ft. (3500 m) in the 14-20-50-12W5 well and the interval from 9250ft. (2819 m) to total depth in the 6-3-51-27W5 well. Maps by Meijer-Drees (1994) show that the closest evaporites in the middle Devonian are about 150 km to the east.

In our paper we pointed out other problems with this thermal convection model: primarily, the fact that the underlying Lobstick Member platform is usually limestone throughout their study area. In contrast, the overlying Blueridge Member is primarily dolomite with anhydrite (an observation not accounted for by their proposed cells). Also, their proposed thermal cells that appear elegant when sketched for one reef, become impossible when one considers that their model requires each of the 30 or so dolomitized pinnacles (2 km spacing) to have its own cell. Machel and Anderson (1989) propose an exotic solution when a more logical one — seepage refluxion — explains the stratigraphic observations better.

In summary, the brines in an open system likely represent the only dolomitizing fluids capable of forming the observed volume of dolomite. The mechanism proposed by us offers a logical way to deliver these brines. Mechanisms proposed by Mountjoy et al. (1999) and Machel and Anderson (1989) do not provide enough magnesium to the system, nor do they honour the observed stratigraphy.

PETROGRAPHY

In their discussion, Machel et al. (2002, this issue) contend petrographic work by Kaufman et al. (1991) refutes our model. In fact, the work supports it. Kaufman et al. (1991) observed at Rosevear Field that low amplitude stylolites and some grain to grain pressure solution predate replacement dolomitization. Based on this observation, Kaufman et al. (1991) argued for dolomitization following “some burial”. We agree with this observation and conclusion. Machel and his colleagues describe work by Lind (1993) and Fabricus (2000) who suggest that 300 to 500 metres of burial is necessary to initiate stylolites. In contrast, Mountjoy et al. (1999) suggest 600 to 1500 m.

Stylolitization is a complex process that depends on many variables such as carbonate grain size, organic content, pore pressure, permeability and pore water chemistry. These variables and their impact are discussed in Choquette and James (1990). Typically, fine-grained limestones and those with higher organic content stylolitize first, and coarser grained limestones stylolitize later. As a result, one must be cautious in assigning a depth to their interpretation, especially the interpretation of the initial, wispy, low amplitude stylolites. Evidence in the literature, e.g. Longman (1981), suggests that pressure solution and stylolitization, especially the formation of low amplitude or “wispy” stylolites, can occur at depths considerably less than 300 metres. Assigning precise depths to stylolites is fraught with potential errors. Consequently, burial depths calculated using degree of stylolitization have large errors.

However, the above arguments are somewhat peripheral to the discussion at hand. The isopach thickness between the Graminia and the dolomitized Swan Hills Formation at Rosevear is about 500 metres. Therefore, without accounting for compaction, the Swan Hills at Rosevear was within the depth range of stylolitization, as suggested by Machel et al.
(2002, this issue), prior to initiation of replacement dolomitization as proposed by us. The stated petrographic observations of Kaufman et al. (1991) are consistent with our model; not evidence of its shortcomings. Wendte et al. (1998) use similar data to argue for intermediate burial prior to the onset of dolomitization in the Swan Hills Formation in the Wild River area.

Petrographic data presented in Figure 6 of Whittaker and Mountjoy (1996) and in Figure 7 of Drivet and Mountjoy (1997) are also consistent with our model. They show that the much more common higher amplitude stylolites postdate dolomitization and support replacement dolomitization prior to significant burial.

Petrographic descriptions of Frasnian replacement dolomite throughout the basin as described by Machel, Mountjoy and their workers (e.g. Amthor et al. 1993), and others (e.g. Kaufman, 1991; Al-Awar, 1996) indicate a strong similarity, suggesting a similar origin. There are two basic replacement dolomite types; fine crystalline and coarser crystalline (Kaufman, 1991). Under plane light the coarser (100-600 micron) replacement dolomite crystals usually consist of cloudy cores with a continuum to clear rims, especially next to pores or fractures. Under cathodoluminescence these crystals have dull cores and zoned rims. The zoned overgrowth can sometimes be correlated to adjacent saddle dolomite cements. Kaufman (1991) and Al-Awar (1996) used these characteristics to argue for overprinting of the replacement dolomite by “later diagenetic fluids” or “neomorphism”, respectively. We have interpreted these dolomites in a similar fashion.

The fine crystalline dolomite is often tightly packed and does not have the clear rims. It usually has more uniform orange-red luminescence. Al-Awar (1996) notes that these dolomites were less neomorphosed (based on heavier isotopic signature) than the more coarsely crystalline, porous dolomites. This may be due to their lack of pore space and more limited access to later diagenetic fluids. He also suggests that microstylolitic pressure solution contacts at Joffre between the crystals in these dolomites supports dolomitization prior to significant burial. Wendte et al. (1998) also describe replacement dolomites with textures that suggest neomorphism.

In summary, the published petrographic data are entirely consistent with the timing and mechanism of our model for replacement dolomite formation. In addition, the petrographic data suggest that significant neomorphism of some of the replacement dolomites has occurred. The implications of this are discussed further below.

**Isotopes**

One of the critical pieces of evidence that Machel et al. (2002, this issue) and others (Drivet and Mountjoy, 1997; Amthor et al., 1993) use in determining the minimum overburden depth during replacement dolomitization are temperatures calculated from oxygen isotopes and assumed geothermal gradients. We will show that alternative interpretations of these data are entirely consistent with our model.

Quantitative analysis of the degree of fractionation of oxygen isotopes can be used as a paleothermometer in the manner outlined by Land (1985) and reproduced as Figure 23 of Allan and Wiggins (1993) and Figure 16 of Kaufman et al. (1991). Land (1985) plotted the relationship of temperature and $^{18}O/_{16}O$ composition of a fluid and the resultant dolomite. It is noteworthy that Land (1985) also suggested that, owing to the inherent uncertainty, this tool should be used in a qualitative and not in a rigorous quantitative manner.

The interpreted crystallisation temperature of the dolomite is extremely sensitive to assumptions of the $^{{18}}O$ of standard mean ocean water of the time period in question. In addition, if neomorphism occurs, the paleothermometer will be reset to reflect the new temperatures and fluid compositions. Allan and Wiggins (1993) discuss this at length, and Amthor et al. (1994) outline some of the pitfalls.

When calculating specific temperatures for dolomite formation using this plot, Amthor et al. (1993) assume that the dolomitizing fluid was “slightly modified Devonian seawater” with about –2.5 per mill $^{{18}}O$. This value is consistent with data from Carpenter and Lohmann (1989) who report that unaltered marine cements from Golden Spike and Nevis Leduc Formation reefs have –5 per mill $^{{18}}O$. These reefs were deposited under normal marine conditions.

Our paleogeographic maps, cross-sections, and stratigraphic description show the extensive and intermittently exposed platforms and brine pools that existed toward the top of the Frasnian second-order succession. Formation of brines would serve to significantly enrich the $^{{18}}O$ (Wiggins and Allan, 1993). We and others observe karsting in several areas. Fluvial, coastal plain siliciclastics are present in the Grosmont complex and in the Nisku Formation (Switzer et al., 1994). It is extremely unlikely that formation fluids resulting under these complex regional conditions would be “slightly modified Devonian seawater”. The present day formation fluids are brines.

An incorrect assumption about initial fluid chemistry will lead to incorrect conclusions about temperature of formation of the dolomite. Even small errors in assumed composition using the chart of Land (1985) leads to large errors in temperature. The mixing of seawater, brines, and meteoric waters that would result under the aforementioned paleogeography would create dolomitizing fluids with a wide range of composition temporally and spatially. Using one value is therefore overly simplistic. In addition, if there has been significant neomorphism of the dolomites, as the petrographic data suggest, the isotopes will have been reset and the results will be meaningless for identifying the characteristics of the parent fluid of the original replacement dolomites.

Mountjoy et al. (1999) realize that this is a potential problem in their discussion of the oxygen isotopes in the Rimbe-Meadowbrook trend. These show an apparent decrease in temperature with depth rather than an increase as expected. They speculate about recrystallisation with fresher, post Devonian waters originating in the Grosmont subcrop or influx of brines at Rimbe to explain this apparent discrepancy. As we
outline above, these problems are not restricted to the Rimby trend alone.

Criticism of this isotopic methodology is not new. Allan and Wiggins (1993), in a discussion of Machel and Anderson (1989), suggest that, based on the methodology, the interpretation of temperature of formation of the pervasive dolomite is “speculative in nature”. They also suggest that the reported range of δ18O falls “mostly within the range of overlap between low temperature and high temperature dolomites” and that as a result, Nisku Formation “pervasive dolomite could have formed at the surface or during shallow burial.” (op. cit., p. 107)

Published δ18O data for the replacement dolomites are plotted as Figure 1. Some previously unpublished data by J. Kaufman and K. Potma for the Swan Hills and Leduc formations in the deep basin have also been included. In order to evaluate these data within a stratigraphic framework, the data are plotted versus depth below the top of the Graminia Formation. Also indicated on the diagram is the expected composition of Frasnian dolomites based on the data of Carpenter and Lohmann (1989). Dolomites formed at 25° Celsius should be 2 to 4 per mill heavier than equivalent calcite (Kaufman, 1991 after Land, 1980). Also plotted are the δ18O data for the dolomite cements. Replacement dolomite data, as classified by the authors, are plotted. The dolomite cements, also as classi-

![Fig.1. A plot of the published oxygen isotope data of Al-Awar (1996), Amthor et al. (1993), Anderson (1985), Drivet and Mountjoy (1997), Duggan et al. (2001), Kaufman et al. (1991), Machel and Anderson (1989), Wendte et al. (1998) and Whittaker and Mountjoy (1996). Also plotted are some unpublished data for the Leduc Formation and the Swan Hills Formation in the deep basin collected by J. Kaufman and K. Potma (Kaufman2). The data are plotted versus depth, in metres, below the top of the Graminia Formation.](image-url)
Also apparent is the wide overlap of lighter replacement dolomites with the later dolomite cements. This reflects recrystallization of much of the earlier-formed replacement dolomites at the progressively deeper burial depths where the cements were formed. Homogenization temperatures of 190°C Celsius reported by Duggan et al. (2001) and 141°C Celsius reported by Wendte et al. (1998) for dolomite cements, and stratigraphic thickness, suggest that the replacement dolomites in the deep basin were buried to 5 or 6 km depth after formation. The Frasnian rocks farthest east experienced slightly shallower burial depths.

The observed progressive depletion of δ¹⁸O with depth is not consistent with the thermoflux model of Wendte et al. (1998). Extensive thermal circulation predicted in their model would serve to diminish the observed trend and form highly depleted dolomites in shallow horizons. Also, they do not report the occurrence of hydrocarbon inclusions in the early-formed dolomites, an expected outcome of early maturation of the Duvernay Formation under their proposed hydrothermal conditions. Kaufman (pers. com.) searched for, but was unable to locate, any hydrocarbon inclusions in replacement dolomites either.

In summary, the use of oxygen isotopes as a paleothermometer for original replacement dolomite formation of the Frasnian in the Alberta basin is speculative. Conclusions about formation of the dolomite at 50 to 60°C Celsius, which points towards a Mississippian age, should be regarded with scepticism, especially since other stratigraphic and mass balance data suggest a different, older age. The wide scatter of the oxygen isotope data, together with regional clustering of data suggest that initial fluid chemistry was complex and that recrystallisation has reset oxygen isotopic ratios. The temperature arguments of Amthor et al. (1993) for 500 to 1500 m of burial and an initiation of dolomitization in the latest Devonian and Mississippian are, therefore, questionable. However, the isotopic data are consistent with the proposed model of early dolomite formation by complex brines, followed by neomorphism upon deeper burial with considerable and variable resetting of the isotopic ratios.

**TIME WINDOW**

We agree with Machel et al. (2002, this issue) that the time window for replacement dolomitization in our model is on the order of 1 million years or less. The impact on dolomitization rates, as open-system refluxion was terminated by initiation of Wabamun Group sedimentation, is uncertain. However, as we illustrate below, this time limit is not a problem. Machel and his colleagues misinterpret what we say in this regard.

In our model, brines of higher than seawater concentration were created on platform interior settings during times of intermittent lowstand and shallow flooding. In this manner, brine was created over much of the basin on the top of Winterburn sequence 2 and 3. These brines could move downward through the section because their density was higher than the Devonian seawater occupying the pore space. It is not a requirement for brines to get from the Grosmont area to the deep basin as Machel et al. (2002, this issue) assert. As shown on Figure 27a of Potma et al. (2001) deep basin reefs are dolomitized from above, by the vertical movement of locally generated brines, not from the eastern part of the province.

Machel et al. (2002, this issue) suggest a reflux rate of 1 m/year, based on work by Kaufman (1994) and Jones and Rostron (2000). This is a misrepresentation of the work of Jones and Rostron (2000, Fig. 4, 6, etc.) who show flow rates of hundreds to thousands of metres per day.

Even if the slower rate of 1 m/yr were used, it would take less than 1000 years for fluids to move from the top of the Winterburn 3 sequence to the base of the Beaverhill Lake at, say, Sturgeon Lake (Potma et al., 2001, Fig. 27a). Similar, simultaneous vertical descent of brines would occur in localities such as along the Killam reef chain, at Bashaw, and in the west basin, where the Winterburn sequences are dolomitized, the Leduc is dolomitized, but the Cooking Lake is limestone. One of the longest transport distances required in our model is the 200 km along the Rimby-Meadowbrook chain where there is an interpreted Ireton aquitard between the Winterburn and the Leduc, and direct vertical movement of brine was impeded. Given the previously stated reflux rate of 1m/yr it would take on the order of 200,000 years to dolomitize the Rimby-Meadowbrook chain. Flow rates may have been higher. Here as well, brines of elevated salinity would be driven by gravity.

**HYDROLOGIC MODELS**

In their discussion, Machel et al. (2002, this issue) present hydrologic arguments against large-scale seepage reflux. In contrast, Kaufman (1994) presents model results that suggest that brine reflux by even slightly evaporated seawater would result in downward and lateral flow of Mg-rich fluids capable of dolomitization. When Kaufman (op. cit.) applied the model to simple depictions of the deep basin part of Alberta, the model showed that refluxing brines generated from above the Nisku Formation could travel downward into the Beaverhill Lake Group.

More recent work by Jones and Rostron (2000) poorly addresses the stratigraphy of their study area. In their model, they show a gentle west-facing ramp covered by normal marine waters with a single point brine entry on the eastern side. This is significantly different from the stratigraphy described by workers such as Oldale and Munday (1994), Switzer et al. (1994), and us. As a result, their model cannot be used to discount seepage reflux as a process for the formation of replacement dolomites in the Frasnian of the Alberta Basin.

A “south-western dip” to the basin in Frasnian time as suggested by Machel et al. (2002, this issue) is not borne out by the Frasnian isopach values reported in Oldale and Munday (1994) and Switzer et al. (1994). These actually indicate thinning over the west Alberta ridge and thickening in the vicinity of Edmonton. The data suggest relative quiescence and basin sag, not a western tectonically-controlled dip.
As for the existence of an open system, paleogeographic maps in Potma et al. (2001) are admittedly poorly constrained in the far west, but illustrate our interpretation of the regime to the west of the west Alberta Ridge. Here, west-facing reef complexes (e.g. western Southesk Cairn complex at Coronation Mountain; Mountjoy, 1978) face into the proto-Pacific. Whether this proto-Pacific was relatively open ocean, or whether it consisted of a series of interconnected normal marine sub-basins is open to conjecture and somewhat irrelevant to the discussion of dolomitization. The work of Richards et al. (1994) suggests that the Prophet Trough was developed by Carboniferous time and that island arc complexes of the Slide Mountain and western terranes had begun to impinge onto the western margin of the Craton. Their Figure 14.1 and our own outcrop observations suggest that the Frasnian ocean basin was not as far west as the Purcell Range, as Machel et al. (2002, this issue) suggest.

In summary, Machel et al. (2002, this issue) have not undertaken hydrologic work that can be used to refute our model or support their own. Models developed to date, other than Shields and Brady (1996) and Kaufman (1994), do not reflect the actual Frasnian stratigraphy.

**SUMMARY AND CONCLUSIONS**

Machel et al. (2002, this issue) summarize 15 years of research by 20 to 25 geologists, geochemists and hydrologists with the following statement: “Pervasive, replacive matrix dolomitization in the Alberta part of the WCSB was accomplished by seawater that was chemically modified, (possibly through some very mild evaporation and certainly through rock-water interaction) to a minor, yet significant, degree and was driven in some hitherto unknown manner through the Devonian strata when they were buried to a depth of 500 m to 1500 m.” In our opinion, this conclusion is unsatisfactory. Rather, the dolomite distribution pattern of pervasive dolomitization of the upper part of the Frasnian sequence, with dolomitization of deeper units where flow paths permit, is compelling data, and points toward the upper Frasnian sequence boundaries as the source of the fluids. A model of early dolomitization by seepage refluxion, followed by deeper burial is also consistent with the petrographic and isotopic data.

There are clearly places where isotopic analysis of dolomites has been useful, such as in the later dolomite and calcite cements described by H. G. Machel, E. W. Mountjoy, their colleagues and other workers (e.g. Kaufman et al., 1989; Wendte et al., 1998). However, we assert that interpretation of the initial temperature of dolomitizing fluids based on the present day isotopic composition of the Frasnian replacement dolomites in the WCSB is potentially erroneous. There were complex initial pore fluids and the significant degrees of burial and subsequent uplift have resulted in significant neomorphism. This is especially true in the absence of a complete stratigraphic framework.

It will be up to future workers to test the seepage reflux model more rigorously and evaluate the hydrologic validity of large-scale brine reflux as applied to the Frasnian of Alberta. Clearly, the issue of dolomite geochemistry and its application to defining original conditions of dolomite formation will be debated for many years to come. Any model for dolomitization must account for the dolomite pattern, the dolomite distribution and the present day geochemistry and petrology of the dolomites. Contrary to the allegations of Machel et al. (2002, this issue) that we have not worked cautiously and critically or included all available data, we assert that our model best meets this test. Machel and his colleagues have yet to present a coherent, unifying replacement dolomitization model for the western Canada Devonian.

In concluding, we thank J. Kaufman for beneficial discussions on the interesting subject of Devonian dolomite over the years, and his and Paul Hemingston’s review of this reply.

**REFERENCES**


Mountjoy, E.W., Jones, G.D. and Rostron, B.J. 2002. Discussion of “Toward a sequence stratigraphic framework for the Frasnian of the Western Canada Basin” by K. Potma, J.A.W. Weissenberger, P.K. Wong, and M.G. Gilhooly. (This issue.)


