ARTICLES

Regional Subsurface Dolomitization: Models and Constraints

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SUMMARY

The "topographic recharge" and "tectonic compaction" models for subsurface fluid flow may have been overapplied to the question of the origin of regional hydrothermal dolomite bodies. These have been attractive models to explain hydrothermal dolomitization because of their obvious applicabilty to the present day hydrology of continental interiors. However, recent modelling studies indicate that topographic recharge does not predict the uniform regional trends of dolomite precipitational temperatures observed in hydrothermal dolomites, and that tectonic compaction requires an unreasonable degree of fluid focusing to achieve precipitational temperatures equal to observed dolomite fluid inclusion homogenization temperatures. Topographic recharge also has the limitation of flushing solutes out of the system, rendering it incapable of further dolomitization. In addition, both topographic recharge and tectonic compaction are unlikely flow mechanisms to explain the origin of extensive open space dolomite cement because of their limited supply of solute.

Thermal convection, on the other hand, can support long-lived flow systems that are capable of recycling subsurface solutions many times through the rock mass. This enhances the opportunity for open space dolomite cementation. Because thermal convection can occur in confined aquifers beneath the sea bed, seawater-derived solutions may be continually added to the convection system. Added seawater would enhance the dolomitization potential of the convection system. The documentation of crustal scale convection systems within subaerially exposed orogenic belts and the outcrop evidence of both upward and downward extending bodies of hydrothermal dolomite adds credence to the hypothesis that thermally driven convective flow occurred within ancient platform carbonates, and may have induced regional hydrothermal dolomitization.

RÉSUMÉ

On a peut-être abusé des modèles explicatifs courants du flux des fluides souterrains dit de recharge topographique, et de compaction tectonique, en les utilisant pour expliquer l'existence de grands ensembles régionaux de dolomies hydrothermales. Sans doute à cause de leur grande utilité en hydrologie continentale on aura présumé que ces deux modèles pouvaient s'appliquer au cas de la dolomitisation hydrothermale régionale. Cependant, des modélisations récentes indiquent que la recharge topographique ne permet pas d'expliquer l'uniformité régionale de la température de précipitation observée dans les dolomies hydrothermales, et d'autre part, la compaction tectonique présuppose l'existence d'un phénomène de convergence des fluides injustifiable permettant d'arriver aux températures d'homogénéisation observées dans les inclusions fluides des dolomies. L'évacuation des produits dissous à l'extérieur du système et qui caractérise le modèle de la recharge topographique, ne permet pas d'expliquer l'existence de phases répétées de dolomitisation. De plus, ni la recharge topographique, ni la compaction tectonique ne sont des modèles de flux capable d'expliquer l'existence de volumes importants de ciments vacuolaires de dolomie.

En contrepartie, le modèle de convection thermale peut très bien expliquer l'existence de systèmes d'écoulement à durée de vie suffisamment longue pour permettre le passage de plusieurs cycles de solutions aqueuses souterraines à travers les masses rocheuses encaissantes. Cette particularité de la convection thermale augmente d'autant les possibilités de formation de ciments vacuolaires de dolomie. N'étant pas confinée au domaine continental, la convection thermale peut agir au sein d'aquifères captifs sous-marins et permettre l'apport continu d'eau marine au système de convection, augmentant ainsi les possibilités de dolomitisation. L'existence documentée de systèmes de convection dans des écailles tectoniques crustales au sein de bandes orogéniques subaériennes, et d'affleurements d'importantes zones de dolomies hydrothermales, autant au-dessus qu'en-dessous du niveau topographique, renforcent l'hypothèse de la présence d'un flux par convection thermique au sein d'anciennes plate-formes de carbonates, phénomène qui pourrait avoir pro-

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voqué une dolomitisation hydrothermale régionale.

INTRODUCTION

"Bandwagons of science can be dangerous vehicles" (Fåhræus, 1996) to use in the pursuit of scientific understanding. Implied in this statement is the perception that some physical models have been applied complacently, or uncritically, to problems concerning the origins of geologic phenomena. Here, we deal with models for the subsurface origin of regionally extensive replacement and hydrothermal dolomites.

Two such models for subsurface dolomitization, the "topographic recharge model" (Fig. 1) and the tectonic overpressure, or tectonically driven, "compaction flow model" (Fig. 2) have gained popularity among researchers in their attempt to explain the origin of many laterally extensive dolomite bodies (*e.g.*, Montañez, 1994; Qing and Mountjoy, 1992, 1994; Amthor *et al.*, 1993; Drivet and Mountjoy, 1997). It is an overstatement to assert that these models are, in fact, geological bandwagons at the present time, but, on the other hand, they are gaining momentum as favored hypotheses to explain diverse occurrences of regional subsurface, or regional hydrothermal dolomitization. Recent mathematical simulation studies, allied with fundamental geological and fluid geochemical data, have shed some light these models, both with respect to theoretical predictions and also with respect to existing data from hydrothermal dolomites, and have exposed some limitations of these models.

Other popular models for regional subsurface dolomitization include burial-compaction dolomitization (Machel and Mountjoy, 1987) and fault-related dolomites (Jones, 1980; Malone *et al.*, 1996). However, these models are more local in scope because of the limited supply of fluids available for dolomitization and dolomite precipitation in the subsurface (Land, 1985; Kaufman, 1994), although some workers have suggested that focusing of burial compaction brines from shale basins may explain the origin of some subsurface dolomites, such as those associated with the Mississippi Valley Pb-Zn deposits of the Tri State District, United States (Gregg, 1985). Malone *et al.* (1996) provide a well-documented study of local hydrothermal dolomitization within a dilational tectonic breccia body, several kilometres long, developed along a strike-slip fault in southern California. This may be an example of hydrothermal dolomitization by the seismic pumping of intraformational fluids during fault movements (*e.g.*, Garven, 1995).

Subsurface dolomites are defined here simply as dolomites precipitated from warm to hot subcritical aqueous solutions in subsurface, or burial, settings after lithification of the host rock. This definition excludes the penecontemporaneous dolomites that typically form in the upper few metres of incompletely lithified sediment during sedimentation (*e.g.*, Perkins *et al.*, 1994). Temperatures of precipitation for subsurface dolomites, including hydrothermal dolomites, range from a low of about 50°C (*e.g.*, Amthor *et al.*, 1993; dolospar in the Leduc Formation of Alberta, Canada) to a high of about 400°C or even higher if pressure corrections for burial are applied to raw fluid inclusion homogenization temperatures (T_h) (*e.g.*, Hulen *et al.*, 1990; dolospar in the Blackburn Oil Field, Nevada, United States). Such high temperatures are greater than the critical temperature for pure water (373°C), but the critical temperatures of aqueous solutions are strongly dependent on salinity, such that extremely hot saline brines like those that precipitated the Blackburn dolospar (~20 wt. % NaCl, Hulen *et al.*, 1990) have critical temperatures in the neigh-

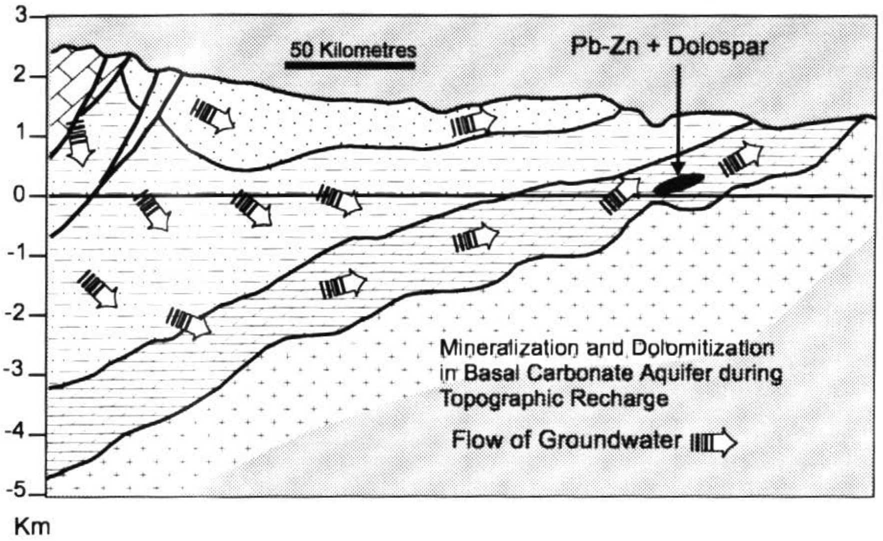


Figure 1 Schematic cross-section view of cross-formational flow during deep circulation of meteoric groundwater by topographic recharge through a typical foreland basin similar to the Western Canada Sedimentary Basin (Garven and Freeze, 1984; reprinted with permission from the American Journal of Science). Flow tends to be focused through more permeable units, such as a basal carbonate aquifer, and has been hypothesized to have caused regional hydrothermal dolomitization (Montañez, 1994; Qing and Mountjoy, 1992, 1994) and mineralization (Garven, 1985).

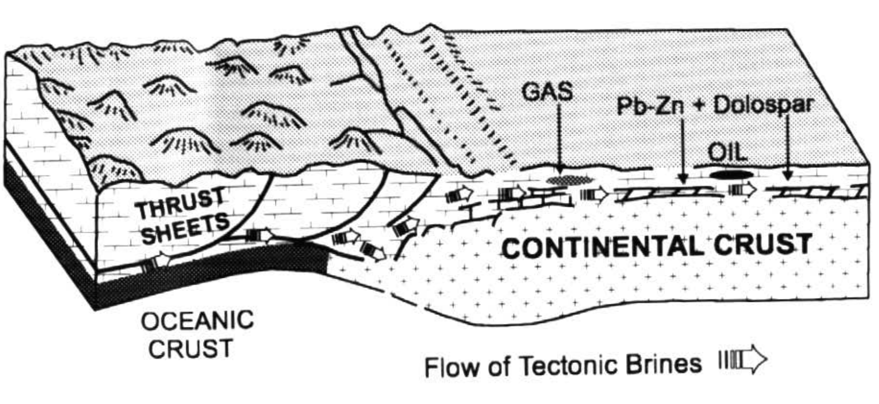


Figure 2 Schematic block diagram of the flow of subsurface fluids in front of a developing compressional orogen. Heated formation fluids are expelled into the foreland belt by tectonic compaction beneath thrust sheets (Oliver, 1986; reprinted with permission from the Geological Society of America) and are thought to have played important roles in regional dolomitization (Amthor *et al.*, 1993; Drivet and Mountjoy, 1996) and mineralization (Oliver, 1986).

borhood of 600°C (Crawford, 1981).

"Hydrothermal" dolomites have no precise definition, but are here considered to be dolomites composed of a large proportion of open space-filling dolospar cement within breccia masses, fractures, or large vugs commonly associated with bodies of subsurface replacement dolomites (*e.g.*, Drivet and Mountjoy, 1997). Implied in this characterization of hydrothermal dolomites is the perception that they were precipitated from circulating geothermal waters.

TOPOGRAPHIC RECHARGE AND REGIONAL SUBSURFACE DOLOMITIZATION

The topographic recharge model of Garven and Freeze (1984) provides a means of moving fluids rapidly through foreland basins in front of thrust belt terrains across distances approaching several hundred kilometres (Fig. 1). The elevated topography of the thrust belt provides the hydrodynamic potential for gravity-driven meteoric fluids to drive groundwater circulation deep into the foreland region. In western Canada, and in the western and central United States, foreland successions are dominantly siliciclastic and are late Paleozoic to Cenozoic in age. These thick foreland successions overlie Paleozoic carbonates that were deformed during the development of the thrust belts associated with Laramide, Antler and Alleghenian, or Ouachita, orogenies (Fig.1).

Subsurface flow tends to be concentrated in the more permeable units of the foreland succession. Commonly, the carbonates that underlie the foreland succession are vastly more permeable, particularly with respect to lateral permeability, than the overlying siliciclastics, and form the principal aquifers. Garven (1994) has pointed out that permeability of carbonates is strongly dependent on the scale of measurement and that even relatively "tight" carbonates can have high overall permeability when measured on a basinwide scale of tens to hundreds of kilometres. Movement of fluids redistributes heat, altering the basinwide temperature regime in the subsurface, and also redistributes solutes within the basin. Under conditions of regional topographic recharge, flow rates can attain average velocities of up to 10 m·a^{-1} in more permeable strata (Garven, 1995). Flow during topographic recharge is generally rapid enough to overwhelm subsurface flow patterns caused by other processes, such as by convection, or by sedimentary and tectonic compaction (Garven, 1995).

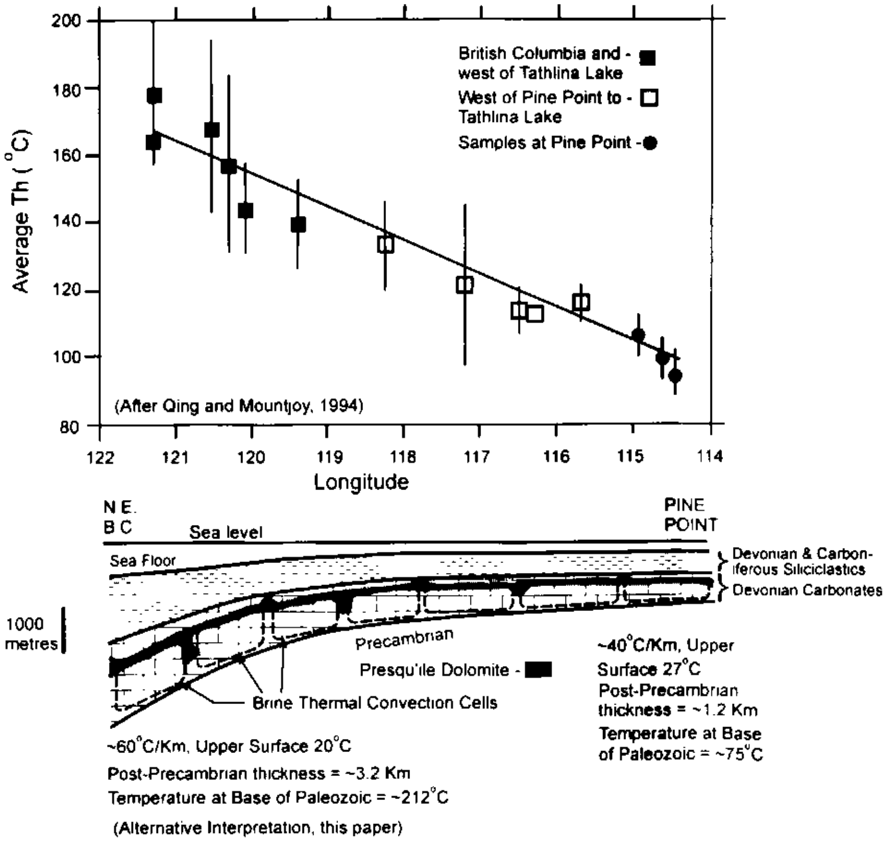


Figure 3 A graph of the progressive westward increase in dolomite fluid inclusion homogenization temperatures within the Presqu'ile Dolomite (after Qing and Mountjoy, 1994). This has been interpreted to indicate an overall west-to-east movement of heated brines during dolomitization (Qing and Mountjoy, 1992, 1994). An alternate interpretation is shown in the lower schematic cross-section in which hotter fluid inclusion temperatures are hypothesized to be the result of deeper convective circulation in western regions where impermeable basement was deeper in late Paleozoic time.

In a landmark study, Garven (1985) applied finite element techniques to demonstrate the potential for topographic recharge to cause deep circulation of groundwater eastward from the elevated thrust belt of the Laramide Orogen of northwestern Canada. Based on this simulation, Garven (1985) suggested that the Pine Point Pb-Zn deposit formed in less than a million years from lead and zinc transported eastward by subsurface solutions focused preferentially through Middle Devonian carbonates of the Keg River Barrier during the post-Cretaceous rise of the Rocky Mountains. Flow rates through the Keg River Barrier reached a maximum of about 5 m·a^{-1} in Garven's (1985) simulation. Garven *et al.* (1993) have also applied the topographic recharge model to the Late Permian of the United States midcontinent region to explain the origin of the MVT Pb-Zn deposits of this region, such as the Viburnum Deposit (*see also* Bethke *et al.*, 1988). Subsurface flow rates of up to 3 m·a^{-1} were modelled in the principal aquifer, the Knox Dolomite, during the Ouachita Orogeny. Modelled subsurface flow during Ouachita topographic recharge also redistributed heat, causing elevated temperatures in the carbonate aquifers at the site of the MVT Pb-Zn deposits near the distal end of the Late Permian foreland belt that developed north of the Ouachita Orogenic thrust belt. These modelled temperatures approximately match the mineral fluid inclusion homogenization temperatures observed in these deposits.

The high rates of fluid flow that are characteristic of the topographic recharge model for groundwater circulation have also made it an attractive choice as a hydrologic model for regional subsurface dolomitization. Qing and Mountjoy (1992, 1994) documented a progressive eastward decrease in fluid inclusion homogenization temperatures of the Presqu'ile Dolomite through the Keg River Barrier from northeast British Columbia to Pine Point at Great Slave Lake, NWT (Fig. 3). They suggested that this approxmately unidirectional trend in homogenization temperatures, in conjunction with similar trends of oxygen and strontium isotopic values, is consistent with the west to east flow of groundwater driven largely by topographic recharge during either the Cretaceous-Tertiary Laramide Orogeny or the earlier Devono-Carboniferous Antler Orogeny. They envisaged basin-scale eastward migration of hot fluids from northeastern British Columbia to Pine Point through the Keg River Barrier driven largely by topographic recharge, but also by tectonic compression, during the Laramide or Antler orogenies and inferred that these fluids were responsible for Presqu'ile hydrothermal dolomitization. Similarly, Montañez (1994) suggested that the migration of hot basinal fluids that caused subsurface hydrothermal dolomitization of the Knox carbonates in the southern Appalachian Mountain region of the eastern United States was facilitated by the development of a regional topographic recharge flow system during the late Paleozoic Alleghenian Orogeny. Topographic cross-formational flow was aided by the upward growth of the Alleghenian highlands, which attained a cumulative tectonic relief of about 5 km. In a more extreme example, Yao and Demicco (1995) have argued that carbonates within the entire pre-Devonian, Neoproterozoic to Silurian succession eastward from the Kootenay Arc of British Columbia to the Front Ranges of the Rocky Mountains were dolomitized during eastward-directed topographic recharge from the region of the Purcell Anticlinorium during mid to late Paleozoic time.

Salinity Constraints

There is no doubt that topographic recharge is extremely efficient at moving fluids and redistributing heat through foreland basins. However, as pointed out by Deming and Nunn (1991), and by Cathles (1993), the circulation of meteoric groundwater quickly sweeps solutes from the basin (Fig. 4). This is the simple consequence of the replacement of saline basinal fluids by dilute meteoric groundwater as it sweeps through the basin. Remnant saline basinal fluids remain only in regions within the basin that were bypassed by the fresh water flush (Fig. 4). The very high salinities of fluid inclusions in hydrothermal and associated subsurface dolomites [*e.g.*, about 15-20 wt.% NaCl equivalent in the Presqu'ile Dolomite (Qing and Mountjoy, 1994): about 13-22 wt.% NaCl equivalent in the Knox Dolomites (Montañez, 1994); mode at 23 wt.% NaCl equivalent in the dolomites of the Mississippi Valley Pb-Zn District (Plumlee *et al.*, 1994); 24 wt. % NaCl equivalent in the dolomite in the Gays River Pb-Zn deposit of Nova Scotia (Chi and Savard, 1995); 22-25 wt. % for hydrothermal dolomites of the Middle Jurassic to Early Cretaceous Arabian Shelf (Broomhall and Allan, 1985); 13-25 wt.% NaCl equivalent for subsurface and hydrothermal dolomites throughout the entire Proterozoic to Silurian succession of the southern Canadian Cordillera (Yao and Demicco, 1995)] is an indication that there has been little, if any, admixture of fresh meteoric water during precipitation of these dolomites. The origin of each of these dolomites depends upon their individual geologic histories, but the consistently high salinities of fluid inclusions in all these examples (and many others) suggest that topographic recharge of fresh water was not

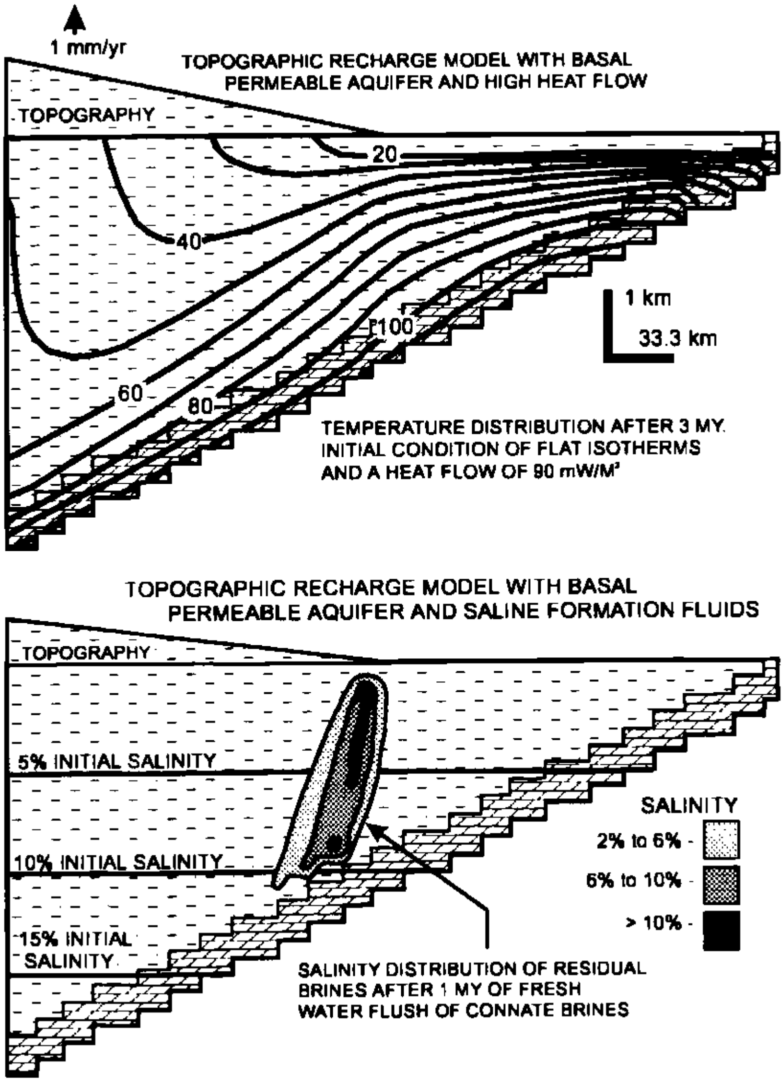


Figure 4 Temperature and residual brine salinity distributions during simulations of topographic recharge through a foreland basin (Deming and Nunn, 1991; reprinted with permission from the American Geophysical Union). Temperature along basal carbonate aquifer tends to be uniform and little residual brine remains after a million years of topographic recharge. The small volume of remaining brine lies within a region bypassed by subsurface fresh water flow.

a dominant hydrologic process during dolomitization.

Mass Balance Considerations

Under the assumption that these basinal fluids participated in the dolomitization of limestone aquifers, it has been estimated that on the order of 350 km^3 of basinal fluids of marine derivation would be required to dolomitize 1.0 km^3 of limestone in these aquifers, depending on limestone porosity and upon exact fluid compositions (Gregg, 1985). This is a stringent, although not impossible, requirement to fulfil by topographic recharge. Conceivably, saline basinal fluids from the siliciclastic foreland succession could be focused into underlying, more permeable carbonates ahead of a basinwide sweep of fresh water and cause the replacement dolomitization of porous limestones in the manner envisaged by Gregg (1985).

Less appreciated are the consequences of the fact that a significant proportion of subsurface hydrothermal dolomites is formed of open space-filling dolospar cement (*e.g.*, Gregg, 1985) precipitated directly from the "dolomitizing" solutions. The fluid requirements for open space precipitation are far more demanding than for *in situ* replacement dolomitization of limestone. For example, using the dolomite cementation model of Leach *et al.* (1991) for hydrothermal dolomite precipitation in the Mississippi Valley Pb-Zn District, 1.0 km^3 of pore space requires 4.878x10^5 km^3 of solution for complete cementation. In other words, to fully cement the pore space of 1 km^3 of carbonate containing a porosity of 2.5% would require, at a minimum, 1.22x10^4 km^3 of solution. In the case of the Mississippi Valley Pb-Zn District, Gregg (1985) estimated that about 100 km^3 of the basal dolomite of the Bonneterre Dolomite was dolomitized during mineralization. If we assume that open space-filling dolomite cement occluded 2.5% of this regional dolomite body, then 1.22x10^6 km^3 of solution would have been required. If these dolomite-cementing solutions were moved by topographic recharge from basinal sediments averaging about 20% porosity, a source sediment volume of 6.1x10^6 km^3 would be required (Fig. 5). Cathles (1993) estimated that the total sediment volume available for fluid expulsion into carbonate aquifers in the Mississippi Valley Pb-Zn District was about 5.56x10^5 km^3, or only a tenth of that required for this scenario.

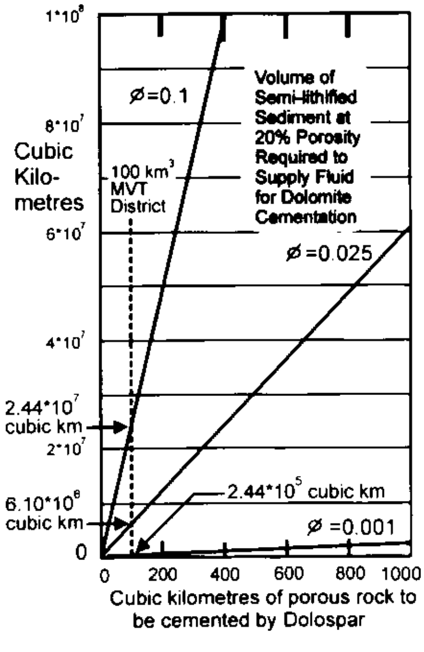


Figure 5 This plot shows the large volumes of basinal sediment-derived fluid that are required to fully cement even low porosity rocks, assuming that each litre of hydrothermal brine precipitates about 10$^{-4.5}$ moles of dolomite from solution (Leach *et al.*, 1991). See text for discussion.

Thermal Constraints

Deming and Nunn (1991) and Nunn and Deming (1991) have discussed thermal constraints concerning the topographic recharge model. In essence, circulation of fresh groundwater, to a first approximation, causes the deeper, originally subhorizontal isotherms to be reoriented more parallel to the regional stratigraphy of foreland basins (Fig. 4). As Deming and Nunn (1991) pointed out, an important consequence of this is that mineral cements formed within carbonate aquifers during topographic recharge would have been precipitated at about the same temperature all along a basal aquifer, except at the very distal end. Pronounced regional trends of more than 50°C in fluid inclusion homogenization temperatures and in temperature-dependent oxygen isotope data (Fig. 3), such as those reported by Qing and Mountjoy (1992, 1994) and Montañez (1994) are not consistent with dolomite cementation during topographic recharge focused along permeable aquifers at depth. Nunn and Deming (1991) also pointed out that the higher flow rates necessary to raise temperatures to the levels (about 80°C to 100°C) indicated by the mineral geothermometers at the shallow (about 1-1.5 km burial depth; Plumlee *et al.*, 1994), distal end of the system, will cause a correspondingly more rapid flush of solutes from the system, as well as a "smoothing out" of regional temperature trends along the basal aquifer.

Cathles (1993) has also modelled the thermal consequences of topographically driven groundwater flow through the Mississippi Valley Pb-Zn District using an elegantly simple analytical expression for temperature perturbations in basins resulting from flow through thin, shallow-dipping confined aquifers (Cathles, 1987). In this simulation of northward flow through the Arkoma Basin and upward through the basal carbonate aquifer of the Mississippi Valley Pb-Zn District (Figs. 6, 7), Cathles (1993) was unable to reproduce the temperatures observed in fluid inclusions of the hydrothermal dolomites, using realistic values of thermal conductivity for the sedimentary cover above the basal aquifer, regardless of groundwater flow rate.

Another important thermal constraint is the necessity for high basal heat flow, in addition to high groundwater flow rates, to raise temperatures near the shallow distal end of the system to be consistent with the correlation between the dolomite and mineral homogenization temperatures of approximately 90°C and cementation at shallow depths. Deming (1992) has speculated that if compressional orogenesis were linked to increases in crustal permeability, basal heat flow could be enhanced to a degree consistent with these high distal temperatures during contemporaneous topographic recharge through the supracrustal sedimentary succession. This is, however, an unproven speculation at present and has not been documented by observation. Instead, observational evidence suggests that basal heat flow is low, rather than high, beneath foreland basins (*e.g.*, Majorowicz and Jessop, 1981).

TECTONICALLY DRIVEN FLOW AND HYDROTHERMAL DOLOMITIZATION

Oliver (1986), in a provocative, and commonly cited paper, brought a previously unappreciated process into the foreground of geological thinking. In this paper, Oliver (1986) described how the process of tectonic loading and compression during the development of orogenic thrust belts may have caused the rapid expulsion of formational fluids outward into the foreland basins with the thrust belts behaving like giant squeegees (Fig. 2). He also suggested that this type of tectonically driven subsurface flow of formation fluids played a major role in the formation of Pb-Zn deposits and hydrocarbon accumulations in carbonate strata of foreland belts.

Tectonically driven groundwater flow has also been cited, either as a contributing factor (*e.g.*, Qing and Mountjoy, 1994; Montañez, 1994; Machel *et al.*, 1996), or as the dominant factor (Amthor *et al.*, 1993; Drivet and Mountjoy, 1997) responsible for the emplacement of some subsurface and hydrothermal dolomites. An attractive feature of the tectonically driven flow model is the fact that, unlike the topographic recharge model, subsurface solutions are not diluted by meteoric recharge during tectonic expulsion. Consequently, compaction flow in general is more consistent with the universal high salinities observed in hydrothermal dolomite fluid inclusions. On the other hand, tectonically driven flow, like subsurface burial compaction flow, is limited to the total volume of fluids within the basin sediments (Garven, 1995). The tectonically driven flow model can be regarded as a special case of compaction flow, in which compaction expulsion is achieved by the rapid tectonic loading of thrust plates moving in front of expanding orogens.

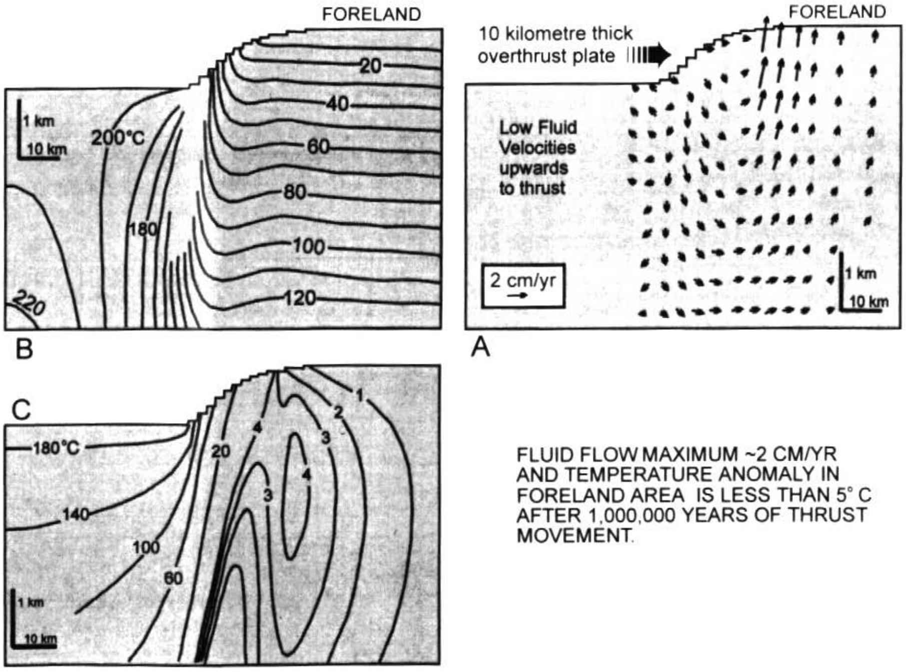
Thermal Constraints

Deming *et al.* (1990), using a finite difference simulation of the effect of thrust belt emplacement on fluid flow and temperature distribution in the foreland belt, found that, under a geologically reasonable range of conditions, tectonically driven compaction results in low velocity and transient groundwater flow with very little influence on the temperature field of the foreland belt (Fig. 6). If flow is channelled into fracture networks that are open to the ground surface however, it is possible to raise temperatures locally to, or even greater than, 50°C above background values (Fig. 7). Mineral cements formed in such fractures would have been precipitated out of thermal equilibrium with host strata (*e.g.*, Dorobeck, 1989). The key factor favoring extreme temperature contrast between the host rock and the mineral cements is that the permeable channelway must be open to the atmosphere. If the channelway is merely open to the sea floor, extreme fluid velocities through the channelway are not possible and again the temperature anomaly will be insignificant.

An even more limiting factor in the use of the tectonically driven flow model is the extreme amount of focusing of flow that must occur to satisfy thermal constraints. Cathles (1993) determined that to warm the updip carbonate aquifer system of the MVT district of the central United States by compaction flow of heated brines from the adjacent Arkoma Basin (Fig. 8) to temperatures equal to observed dolomite homogenization temperatures requires flow rates of 4.4-17.6 $m \cdot a^{-1}$ (Fig. 9). These are more than an order of magnitude greater than modelled or observed flow rates due to compaction flow caused either by sedimentation (Bethke, 1985; Garven, 1995), or by tectonic loading (Deming *et al.*, 1990), even if geologically reasonable permeability heterogeneity is considered. It is unclear how such an extreme degree of fluid focusing can occur. Also, at these extreme flow rates, compaction fluids in the Arkoma Basin (Fig. 8) would be exhausted in a few hundred thousand years.

Mass Balance Considerations

Another limitation, as discussed above, concerns the amount of solution required to dolomitize the MVT district carbonates. Cathles (1993), following Gregg (1985), estimated that 35,000 km^3 of brine would be required to explain the observed amount of dolomitization. This estimate, however, does not take into consideration dolomite precipitated as open space-filling cement. If only 0.1% of the rock mass in this carbonate aquifer system were precipitated as space-filling dolospar, there would be an additional requirement for $4.878 \cdot 10^4$ km^3 of solution (Fig. 5). This means that nearly 15% of the total Arkoma basin sediment volume would have to be derived from the basin as compaction flow fluids, rather than the 6% estimated by Cathles (1993). This is close to an unreasonable requirement for the total volume of compaction flow that could be expressed from the Arkoma Basin. The larger the estimated amount of open space-filling dolospar in the system, the more unreasonable this requirement becomes. This model is more reason-



FLUID FLOW MAXIMUM ~2 CM/YR AND TEMPERATURE ANOMALY IN FORELAND AREA IS LESS THAN 5° C AFTER 1,000,000 YEARS OF THRUST MOVEMENT.

Figure 6 Plots of modelling results for the tectonic compaction model assuming uniform horizontal and vertical permeabilities (Deming *et al.*, 1990; reprinted with permission from the American Geophysical Union). Diagram B shows the total temperature distribution and diagram C shows a residual temperature distribution beneath and in front of an orogenic thrust sheet. The residual temperature is the total temperature minus the equilibrium temperature of the foreland succession before the arrival of the thrust sheet.

ably applied to examples in which the total volume of dolomite cement is low (*e.g.*, Machel *et al.*, 1996).

CONVECTION AND HYDROTHERMAL DOLOMITIZATION

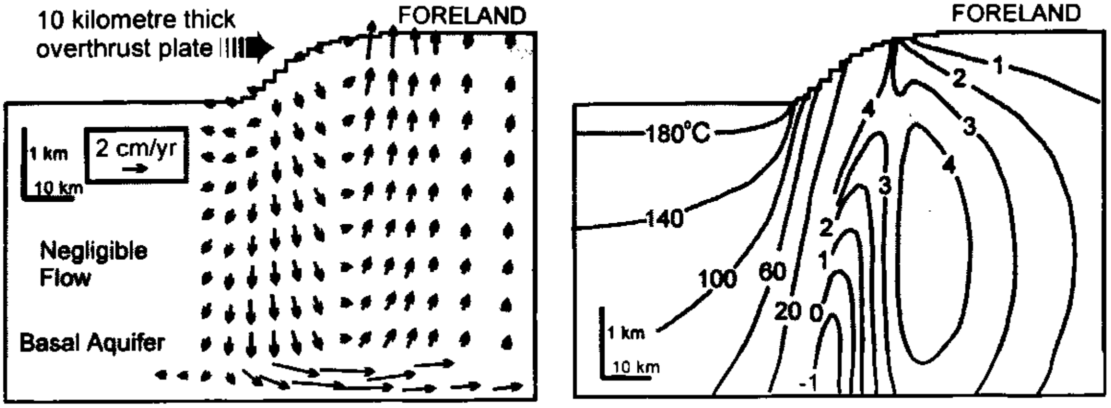
Free convection in subsurface sedimentary settings (Fig. 10) is driven by buoyancy forces related to temperature and salinity variations (Garven, 1995). Flow rates in convection cells can approach a metre per year depending upon aquifer thickness, fluid-density gradient, and regional permeability (Evans and Nunn, 1989). A fundamental relationship exists between the thermal gradient required for convection in a porous layer and the permeability and thickness of the layer within which convection can potentially occur for subhorizontal strata. This relationship may be expressed as:

$$\frac{dT}{dz} = \frac{\mu \bullet \lambda_m \bullet Ra_{cr}}{\alpha_f \bullet \rho_f^2 \bullet c_f \bullet k \bullet b^2} \tag{1}$$

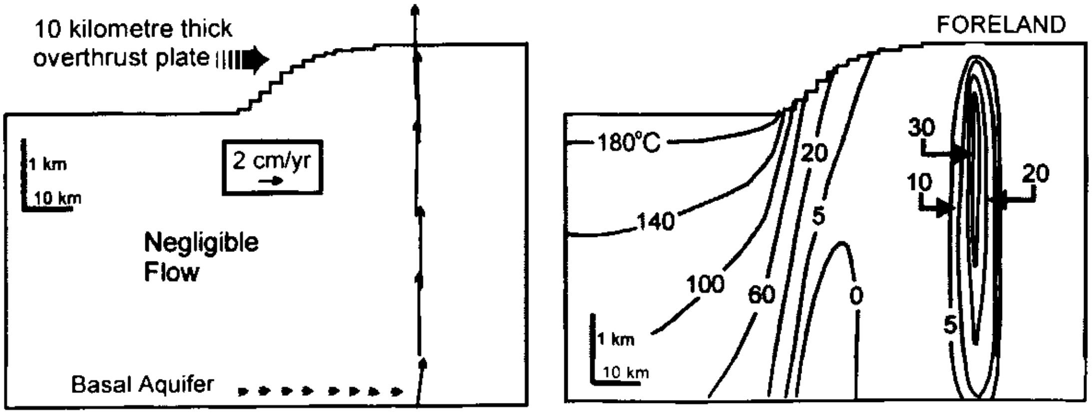
(Turcotte and Schubert, 1982), where dT/dz is the geothermal gradient, μ is the kinematic fluid viscosity, λ_m is the bulk thermal conductivity of the convecting layer. Ra_{cr} is the minimum critical Raleigh number required to initiate convection within a layer of thickness b and permeability k, and is a constant equal to $4\pi^2$. The fluid co-efficients of thermal expansion and of specific heat are α_f and c_f, and the fluid density is ρ_f.

There is a strong dependence on layer thickness in Equation 1. For a reasonable range of possible geothermal gradients (10°C·km^{-1} to 100°C·km^{-1}), a 200 m-thick layer in which convection can occur must have an average permeability of between about 100-1000 millidarcies. For a layer that is 1000 m thick and the same range of geothermal gradients, the minimum permeabilities required for the onset of convection are reduced to a range of about 6-60 millidarcies (Turcotte and Schubert, 1982).

There is also a strong dependence on fluid density in Equation 1. The permeabilities required for convection to begin, as cited in the previous paragraph, would be reduced by about 30% if halite-saturated brine with a specific gravity of 1.2 gm·cm^{-3} (Spencer, 1987) were the convecting fluid instead of pure water. Solving Equation 1 for the Raleigh Number (*Ra*) shows the direct dependence of convection on the geothermal



MAXIMUM FLUID VELOCITY - 3.8 CM/YR BUT VERY SMALL FORELAND THERMAL ANOMALY (<5°C)



SUBVERTICAL FRACTURE ZONES MAY CONTAIN HIGH TEMPERATURE DOLOMITE CEMENTS

Figure 7 Plots of modelling results for the tectonic compaction model assuming different permeability structures (Deming *et al.*, 1990; reprinted with permission from the American Geophysical Union). The upper diagrams show the fluid flow pattern and residual temperatures that develop during thrusting over a foreland succession with a basal permeable aquifer. The lower diagrams illustrate the influence of a high permeability channelway that is open to the surface.

gradient itself. Equation 1 is also subject to the *proviso* that the regional dip is less than a critical angle of about 5°. In more steeply dipping strata, convection, at rates depending primarily on permeability and the geothermal gradient, will occur invariably (Criss and Hofmeister, 1991).

Convection has been less popular than the topogaphic recharge or the tectonic compaction models as an explanation for regional hydrothermal dolomitization. Deep convection circulation of hydrothermal brines has been invoked to explain the origin of only a few regional subsurface hydrothermal dolomites, such as the Manetoe Dolomite of the Northwest Territories (Morrow *et al.*, 1986, 1990; Aulstead *et al.*, 1988) and the Ordovician gas-producing carbonates of the Michigan Basin (Coniglio *et al.*, 1994). Other workers have suggested that pre-Cretaceous thermally driven convective flow is unlikely to have occurred over large parts of the Western Canada Sedimentary Basin because of the absence of any indication of pre-Cretaceous thermal anomalies (*e.g.*, Amthor *et al.*, 1993).

The fact that the convection model for fluid circulation has received comparatively little attention with regard to regional dolomitization may be attributed to several factors. First, the present-day deep circulation of groundwater in the sedimentary basins of western Canada and the United States is perceived to be dominated by topographic recharge flow (Garven, 1995). Application of the topographic recharge model to the question of origin of ancient regional subsurface and hydrothermal dolomites follows a principal axiom of geoscience, that the present is the key to the past. In a similar vein, the tectonic compaction flow model is linked to the development of mountain belts, both ancient and present. It is easily assumed that the emergence of these mountains was accompanied by equally impressive subsurface fluid movements. In other words, the present-day manifestations of the topographic recharge and tectonic compaction models have, to a certain extent, pre-empted consideration of the convection model.

Some modelling studies, however, indicate that regional thermal convection may explain the origin of unconformity-type Proterozoic uranium deposits. In the study of Raffensperger and Garven (1995), convection cells 10-50 km broad drove fluids 3-6 km vertically at up to 1.0 $m \cdot a^{-1}$ through sandstone aquifers with horizontal and vertical permeabilities of 160 and 1.6 millidarcies. Carbonate aquifers on a regional scale can have permeabilities of more than 100 darcies owing to the presence of fracture networks and karst porosity (Garven, 1994; Domenico and Schwartz, 1990) and therefore, on a regional scale, are candidates for thermal convection. Kaufman (1994) modelled thermal convection through platform carbonates hundreds of metres thick, and suggested that subsurface dolomitization in continental shelf settings could occur as a consequence of the development of large convection cells in response to spatial variations in basal heat flow.

The dolomitized Mesozoic carbonate buildups, or platforms, of northern Italy provide some excellent examples of hydrothermal dolomitization by convection of seawater on a subregional scale of kilometres to tens of kilometres wide (Wilson *et al.*, 1990; Cervato, 1990). The Latemar Buildup, documented by Wilson *et al.* (1990), is a particularly compelling example of this type of hydrothermal dolomitization where heated seawater has dolomitized a mushroom-

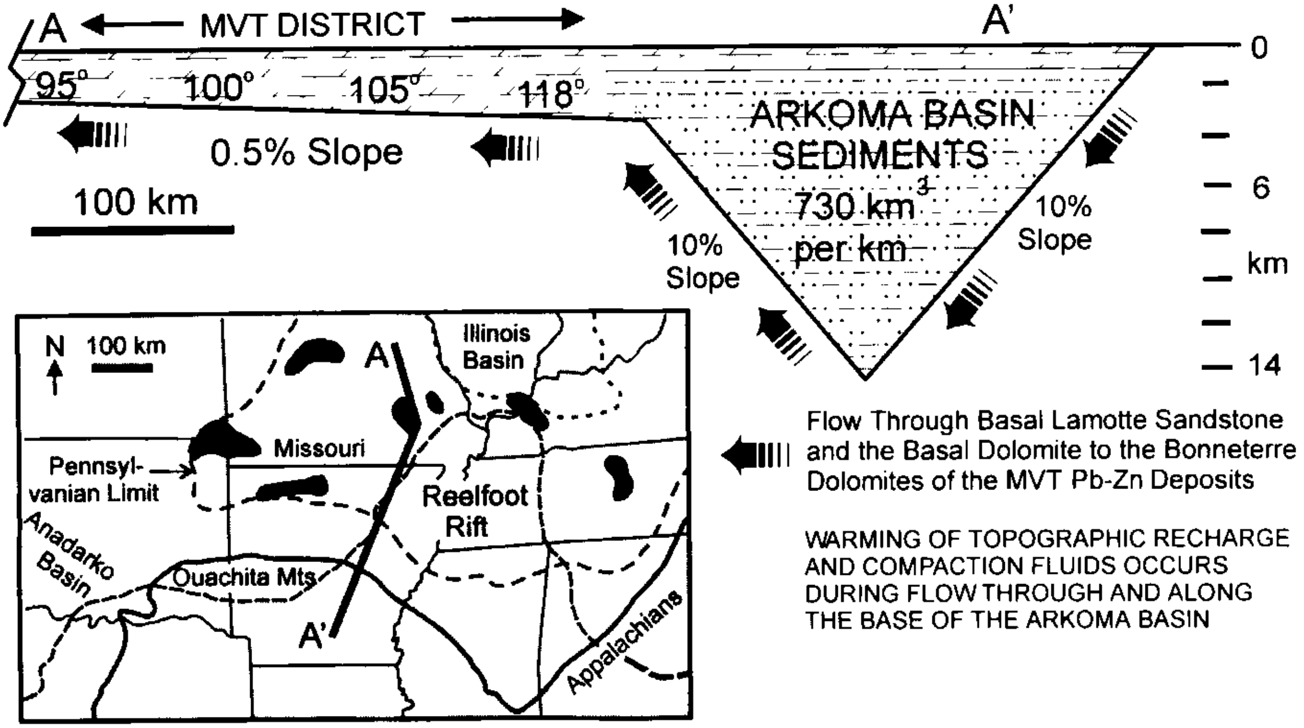


Figure 8 A schematic cross-section from the Arkoma Basin through the Mississippi Valley MVT Pb-Zn District showing the possible northward flow path of compaction and topographic recharge fluids from the Ouachita Mountains during the late Paleozoic Alleghenian Orogeny of the south-central United States (Cathles, 1993; reprinted with permission from the American Association of Petroleum Geologists). Fluids are warmed during their passage downwards through the Arkoma Basin. Also shown are typical sphalerite and dolomite fluid inclusion temperatures across the MVT Pb-Zn District.

shaped body of limestone with a core of hydrothermal dolomite-cemented breccia (Fig. 11).

Evaporative brines derived from the Elk Point Basin in Devonian time have been suggested as the dolomitizing agents responsible for hydrothermal dolomitization across western Canada by subsurface convection in Late Devonian time (Spencer, 1987). Similar systems operate on more local scales at the present time. In one of these, the Salton Sea Geothermal system, dense hypersaline brines of the Salton Sea have sunk up to 5 km into the subsurface and have been recirculated to shallow depths by convection associated with increased basal heat flow related to the opening of the Gulf of California (McKibben *et al.*, 1987).

Mass Balance Considerations

Like the topographic recharge and tectonic compaction models, the convection model operates with the same minimum requirement of magnesium for dolomitization of pre-existing limestone. Because the convective system continually recycles these brines through the pore networks of dolomitizing limestones, however, there is an enhanced potential for more complete open space cementation to occur. The other models permit only one pass of the brine solutes through the system and thus have a much lower potential to precipitate large masses of dolomite cement.

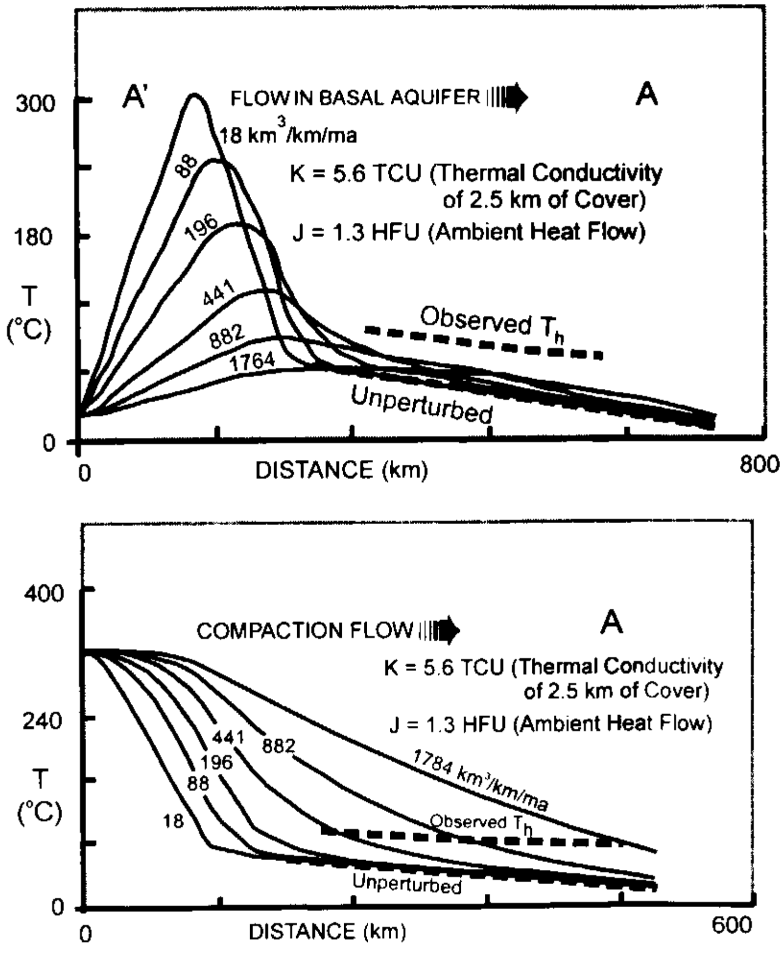


Figure 9 Plots showing temperature variations along the flow path for topographically driven recharge and compaction flow northward along the line of section A'-A shown in Figure 8 for six different flow rates. Topographic recharge fluids begin at surface temperature and warm to a maximum at the base of the Arkoma Basin and then rise upwards through the carbonate and sandstone aquifers of the MVT Pb-Zn District. Under reasonable conditions of sedimentary cover, thermal conductivity and basal heat flow, none of these flow rates is compatible with the observed mineral fluid inclusion temperatures (T_h). The temperature history of compaction flow begins at the bottom of the Arkoma Basin at 325°C. Only high rates of compaction flow can generate temperatures equal to mineral fluid inclusion temperatures, and fluids must be progressively more focused along the flow path to achieve the observed distribution of inclusion temperatures (Cathles, 1993; reprinted with permission from the American Association of Petroleum Geologists).

If convective recycling of evaporative seawater-derived brines occurs while additional hypersaline brines are generated in updip regions on the surface, the potential exists for additional pore volumes of brine to pass through the system, providing that these brines can also exit from the system. Mass movement of brine through the system might occur if the base of the convection system slopes basinward (Fig. 3), as, for example, in the Late Devonian of western Canada where brines continued to be generated up to latest Devonian time (*e.g.*, Whittaker and Mountjoy, 1996). Even in a brine convection system that is closed to addition of brine, mixing of the brines with shallow seawater-derived subsurface fluids immediately overlying the system might also be a means by which small amounts of magnesium are continually added to the convecting solutions that have been depleted in magnesium by dolomitization of limestone and by dolomite cementation (Fig. 10). Dissolution of preexisting dolostones is another source for the magnesium required for dolomite cementation during convection-driven solution movement.

DISCUSSION

There are several difficulties concerning the application of the popular topographic recharge and tectonic compaction models to the problem of the origin of regional subsurface dolomite. Some of these have already been discussed, such as the limitation of the total mass of solutes in the system to one pore volume in both of these models, the inability of these models to predict the cementation temperatures of regional subsurface dolomites, and the probability that neither model can predict the amount of open space-filling hydrothermal dolomite cement that is present in regional subsurface dolomites, even if only a small fraction of these dolomites is formed of dolomite cement.

Another crucial limitation concerns the observation that stratigraphic successions containing some well-studied regional dolomites are suffused with connate hypersaline brines (*i.e.*, original formation fluids) at the present time. This applies to the Elk Point Group of the Western Canada Sedimentary Basin including the Presqu'ile Dolomite along the Presqu'ile Barrier (Bachu, 1995; Bachu, 1997; Spencer, 1987) and in the Paleozoic succession containing the regional hydrothermal dolomites that host the Mississippi Valley-type Pb-Zn deposits of the Tri-State District (Cathles, 1993). This clearly implies that these successions were not flushed by meteoric water during topographic recharge before the present day (*e.g.*, Connally *et al.*, 1990), rendering the use of topographic recharge as a fluid flow model for dolomitization inappropriate in these instances.

Another aspect of regional subsurface and hydrothermal dolomites that has received attention is that they display regional trends in fluid inclusion homogenization temperatures and stable and radiogenic isotopes (Qing and Mountjoy, 1994; Cathles, 1993). As discussed above, modelling studies have shown the difficulties inherent in interpreting these trends as simple indicators of subsurface fluid paleoflow directions during topographic recharge or tectonic compaction (Deming and Nunn, 1991; Deming *et al.*, 1990; Cathles, 1993).

Vertical recycling of connate formation brines by thermal convection may provide a reasonable alternative explanation for the origin of some regional subsurface dolomites that circumvents some of the difficulties inherent in the application of the topographic recharge and tectonic compaction flow models. The most obvious advantage of thermal convection is the continual recycling of subsurface brines through the system, providing a greater opportunity for coarse space-filling dolospar crystals to grow. The dense, halite-saturated residual brines produced during deposition of the Prairie Evaporite in the Elk Point Basin of western Canada contained more than enough magnesium to form all Devonian dolomite in this basin (Spencer, 1987; Shields and Brady, 1995). Open space-filling dolospar (*e.g.*, saddle dolomite) constitutes only a portion of these dolomites.

In thermal convection regimes, fluid inclusion and isotopic paleotemperature trends may reflect basement depth gradients rather than flow directions. In the example provided by Qing and Mountjoy (1994) of the Presqu'ile Dolomite along a transect from Pine Point southwestward to northeast British Columbia, the base of the Paleozoic in latest Devonian to Early Carboniferous time was inclined westward (Fig. 3). Using conservative estimates of the geothermal gradients (Morrow *et al.*, 1993; Morrow and Gallagher, in press) and estimates of burial depths (Meijer-Drees, 1993) for these areas during late Paleozoic time, the temperature at the base of the Paleozoic in latest Devonian to Early Carboniferous time can be roughly determined (Fig. 3). If convection were rapid, dolomite cements formed within the convection system should, to some degree, reflect these trends in basement temperatures. The hotter paleotemperatures recorded in the Presqu'ile Dolomites of British Columbia may simply be a function of the greater depth to Precambrian basement in Latest Devonian time.

Paleozoic time in general may have been favorable for the development of

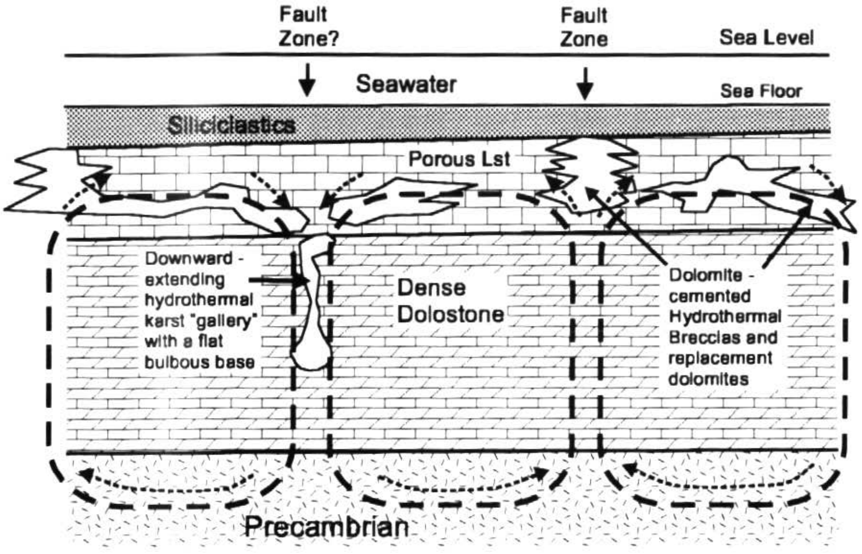


Figure 10 Schematic cross-section through part of a regional convection system within a typical Paleozoic sedimentary succession of dense peritidal calcareous dolostone overlain by porous limestone and capped by upper Paleozoic, fine grained siliciclastics. Stratiform dolomite-cemented breccia forms within the subhorizontal parts of the convective flow path, whereas in regions of strong upward flow at the junction of the upward-flowing parts of adjacent convection cells, dolomite breccias extend upward to the upper contact of the limestone with the overlying less permeable siliciclastics. In regions of downward flow, anastomosing, flat-bottomed galleries of dolomite and calcite-cemented breccias extend downward into the lower dense dolostone sequence. Upward and downward flow may be focused preferentially along fault zones (Morrow *et al.*, 1990).

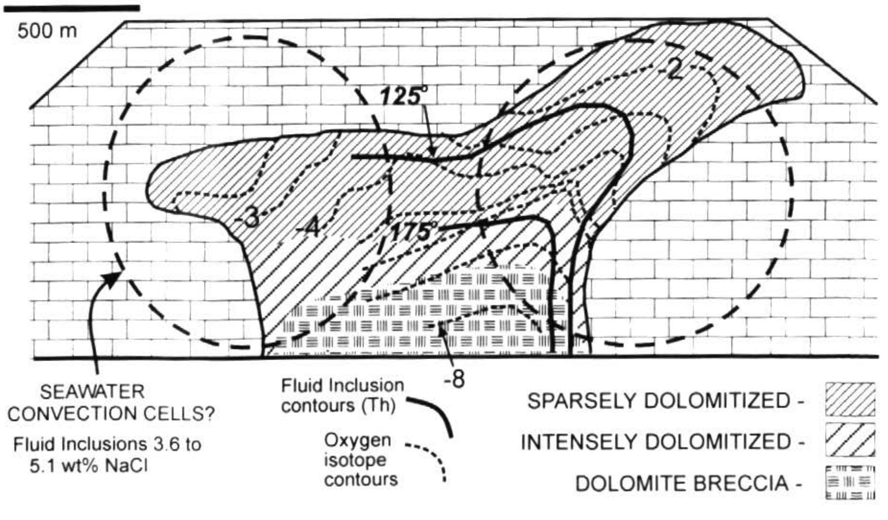


Figure 11 A typical mushroom-shaped breccia-cored hydrothermal dolomite body developed within the Triassic Latemar Platform of the Italian Alps. Trends in fluid inclusion homogenization temperatures (Th) and oxygen isotope values, and the fluid inclusion melting temperatures indicate that dolomitization occurred during the thermal convection of seawater through the Latemar Platform (Wilson *et al.*, 1990; reprinted with permission from the American Journal of Science).

convection systems because of the prevalence of broad, low relief or shallow water carbonate shelves. In western Canada and the western United States, lower Paleozoic cabonate shelf "platforms" are overlain uniformly by blankets of Upper Devonian to Carboniferous siliciclastics which probably acted as cool, relatively impermeable, confining layers to the upward flow of hot formation fluids (Fig. 10). Cervato (1990) discussed a similar example from the Jurassic-Cretaceous of the Italian Alps in which platform carbonates were dolomitized probably during thermal convection of seawater-derived solutions beneath an impermeable cap of volcaniclastic sediments across a marine platform 50 km wide.

Convection may have been initiated by high heat flow in late Paleozoic time, possibly coinciding with times of rifting, which affected large areas of northwestern Canada (Morrow *et al.*, 1993; Feinstein *et al.*, 1996). Other regions which may have been affected by high heat flow in late Paleozoic time include the Michigan Basin region of the United States (Vugrinovich, 1988) and the Upper Silesian Basin of Central Europe (Safanda *et al.*, 1991). Estimated late Paleozoic geothermal gradients in these areas range from about 50°C·km^{-1} (Feinstein *et al.*, 1996) to the very high value of 95°C·km^{-1} (Safanda *et al.*, 1991). Such high geothermal gradients favour the initiation of convection in subhorizontal strata. If permeability in Equation 1 is considered to be a variable dependent only upon the geothermal gradient for the initiation of convection, it is apparent that an increase in the geothermal gradient will be matched by a corresponding decrease in the minimum required permeability for convection to begin.

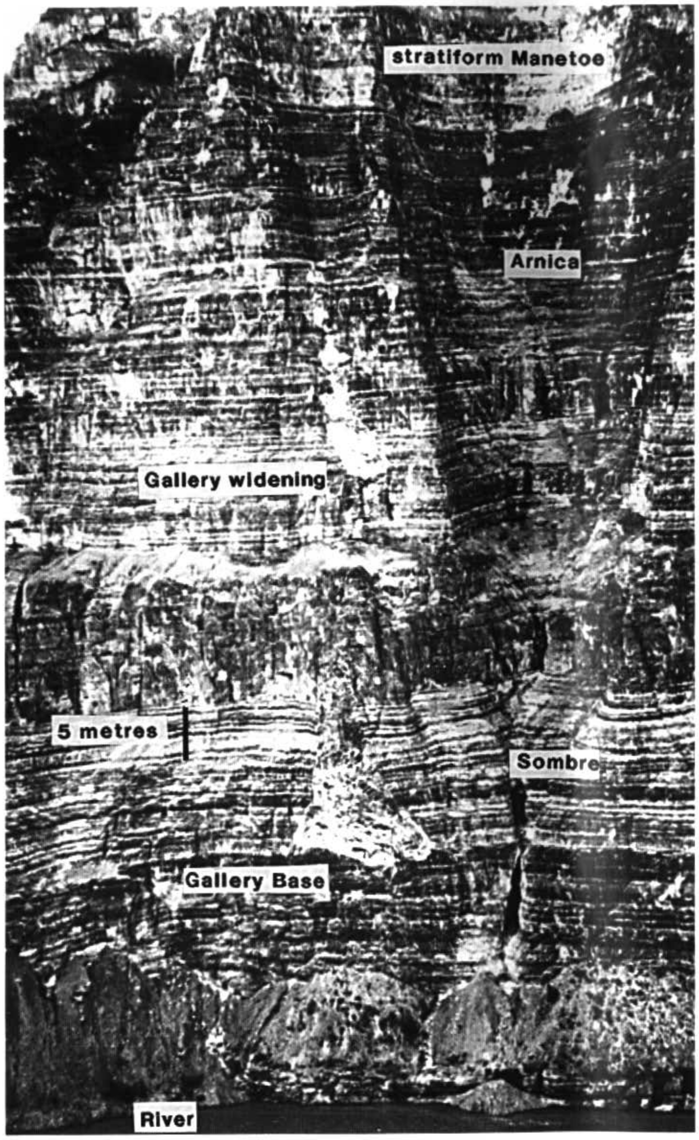


Figure 12 Outcrop photograph of a large, subvertical gallery of white, dolomite- and calcite-cemented breccia extending over a hundred metres downwards from the main body of stratiform Manetoe Dolomite. The gallery ends downward in a rather bulbous, flat-bottomed breccia mass. Some breccia blocks can be correlated with the adjacent wall rock. View is of the northeast side of First Canyon of the South Nahanni River near the west end of the canyon. River level is at the bottom of the photograph.

The question of whether thermal "anomalies" have occurred during the late Paleozoic or early Mesozoic is difficult to answer for some regions because of the absence of strata of these ages. This applies to large parts of the Western Canada Sedimentary Basin where Cretaceous-aged strata unconformably overlie Devonian strata (Mossop and Shetsen, 1994). In general, the presence of thermally immature strata overlying regionally dolomitized carbonates does not preclude thermal convection prior to, or even during, deposition of the overlying strata. It is the geothermal gradient that determines whether convection will, or will not, occur. Even with high geothermal gradients, several hundred metres of siliciclastic strata overlying convection systems in carbonates may not be heated to temperatures in excess of those produced by subsequent burial. Objections, such as those raised by Amthor *et al.* (1993), to the possibility of regional late Paleozoic convection in the southern part of the Western Canada Sedimentary Basin, are not decisive in this regard.

The circulation of fluids in a regional convection system may leave a visible imprint on the host strata in the form of breccia masses cemented by white dolospar, or saddle dolomite. Coniglio *et al.* (1994) suggested that subvertical bodies of dolomite-cemented breccia and dolomitized limestone developed around faults in lower Paleozoic limestones of the Michigan Basin by vertical flow during late Paleozoic to early Mesozoic convection. Figure 10 is a schematic view of hydrothermal dolomite bodies developed within a Paleozoic stratigraphic succession similar to that which contains the Presqu'ile and Manetoe Dolomites of northwest Canada. These hydrothermal dolomite masses tend to be stratiform within Lower and Middle Devonian limestones over broad areas, but, at certain places, such as at the Pine Point Pb-Zn deposit, or in the Pointed Mountain Gas Field, these hydrothermal dolomites extend upward through these limestones (Slave Point, Sulphur Point, Nahanni and Landry formations) toward their contacts with overlying shales. Whatever the origin of these dolomites, it is evident that these upward-extending dolomite breccia masses in the Presqu'ile and the Manetoe are sites where upward flow of hydrothermal solutions was particularly vigorous. Commonly these sites are located along regional faults, such as the McDonald Fault Zone and the Liard Fault Zone (Qing and Mountjoy, 1994; Morrow *et al.*, 1990).

Convection flow may also leave leave an imprint of downward flow as well as upward flow in convection systems that occupied several kilometres of strata. The Manetoe Dolomite of the Northwest Territories is a well-exposed example of what may be a fossilized convection system that formed one of the largest continuous hydrothermal dolomite bodies on Earth. Downward-extending galleries, filled with dolomite- and calcite-cemented breccia, are visible in places with sufficiently large exposures of the peritidal dolostone sequence beneath the stratiform Manetoe Dolomite (Fig. 12). These sharp-walled galleries, up to 150 metres in vertical extent, terminate downwards in bulb-shaped, rather flat-bottomed masses of dolomite breccia. These downward-extending breccia bodies occur in areas where there are no upward-extending bodies of Manetoe Dolomite.

Downward-extending galleries of dolomite breccia may be overt evidence indicating the existence of the downward-flowing parts of convection cells responsible for the Manetoe hydrothermal dolomitization event (Fig. 10). The geometry of these breccia bodies is similar to the vertically oriented and downward widening galleries that develop in vertically fractured limestones undergoing the early stages of meteoric karst development (Jakucs, 1977). However, it is unlikely that these Manetoe galleries have a meteoric karst origin because the microstratigraphy of dolostone blocks cemented within the breccia mass can be correlated with the enclosing color-banded dolostones (Fig. 12). Excavation of the gallery appears to have been contemporaneous with both the collapse of dolostone blocks from the wallrock into the gallery, and with their cementation by coarsely crystalline white dolomite and calcite.

Interestingly, pervasive deep crustal scale convection of meteoric groundwaters in a system that extended downward from the surface to 10 km depth appears to have been the dominant subsurface flow system in the Omenica extensional complex and adjacent parts of the Rocky Mountains during Early Tertiary time (Nesbitt and Muehlenbachs, 1995). These workers speculated that subvertical fracture networks opened during Eocene extension of the Omenica Belt and provided the vertical permeability necessary for convection of fluids in the upper crust. If true, this would be an example of convection within a subaerially exposed mountainous terrain that by conventional wisdom should be part of a topographic recharge system. It does not require an overactive imagination to suggest that large-scale convection may have occurred within rifted Paleozoic or Mesozoic shelf carbonate sequences if large-scale thermal convection can also occur within subaerially exposed mountain belts!

CONCLUSIONS

The topographic recharge and tectonic compaction models may have been over-applied to the question of the origin of regional subsurface dolomites. Topographic recharge does not predict the uniform regional trends of dolomite precipitational temperatures observed in hydrothermal dolomites, and tectonic compaction requires an unreasonable degree of fluid focusing to achieve dolomite precipitational temperatures. Topographic recharge rapidly flushes solutes out of the system, rendering the system incapable of further dolomitization. Both topographic recharge and tectonic compaction are unlikely flow mechanisms to explain the origin of extensive open space dolomite cement because of the limited supply of solute.

Thermal convection, on the other hand, can support long-lived flow systems that are capable of recycling subsurface solutions many times through the rock mass. This greatly enhances the opportunity for open space dolomite cementation. Because thermal convection can occur in strata beneath the sea bed, there is a reasonable expectation that seawater-derived solutions would be continually added to the convection system. These added solutions would enhance the dolomitization potential of the convection system. The documentation of crustal scale convection systems within subaerially exposed orogenic belts and the outcrop evidence of both upward and downward extending bodies of hydrothermal dolomite adds credence to the hypothesis that thermally driven convective flow occurred within ancient platform carbonates and may have induced regional hydrothermal dolomitization.

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