
Genesis of self-organized zebra textures in burial dolomites: Displacive veins, induced stress, and dolomitization

E. MERINO^{|1|} A. CANALS^{|2|} and R.C. FLETCHER^{|3|}

^{|1|} Department of Geological Sciences, Indiana University
Bloomington IN 47405, USA. E-Mail: merino@indiana.edu

^{|2|} Dpt. Cristal·lografia, Mineralogia i Dipòsits Minerals, Facultat de Geologia, Universitat de Barcelona
Martí i Franquès, s/n, 08028 Barcelona, Spain. E-Mail: angelscanals@ub.edu

^{|3|} Department of Geosciences, Pennsylvania State University
University Park, PA 16802, USA. E-Mail: rfletche@geosc.psu.edu

ABSTRACT

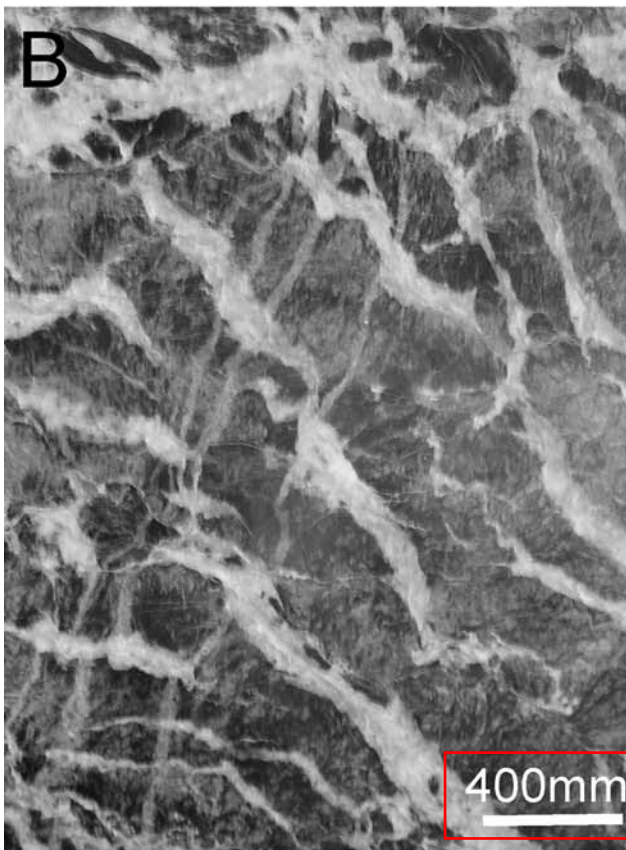
The dolomite veins making up rhythmites common in burial dolomites are not cement infillings of supposed cavities, as in the prevailing view, but are instead displacive veins, veins that pushed aside the host dolostone as they grew. Evidence that the veins are displacive includes a) small transform-fault-like displacements that could not have taken place if the veins were passive cements, and b) stylolites in host rock that formed as the veins grew in order to compensate for the volume added by the veins. Each zebra vein consists of crystals that grow inward from both sides, and displaces its walls *via* the local induced stress generated by the crystal growth itself. The petrographic criterion used in recent literature to interpret zebra veins in dolomites as cements - namely, that euhedral crystals can grow only in a prior void - disregards evidence to the contrary. The idea that flat voids did form in dolostones is incompatible with the observed optical continuity between the saddle dolomite euhedra of a vein and the replacive dolomite crystals of the host. The induced stress is also the key to the self-organization of zebra veins: In a set of many incipient, randomly-spaced, parallel veins just starting to grow in a host dolostone, each vein's induced stress prevents too-close neighbor veins from nucleating, or redissolves them by pressure-solution. The veins that survive this *triage* are those just outside their neighbors's induced stress haloes, now forming a set of equidistant veins, as observed.

KEYWORDS | Rhythmite. Zebra texture. Breccia texture. Displacive Veins. Induced stress. Self-organization. Burial dolomitization.

INTRODUCTION

Zebra textures, or rhythmites, occur in bodies one to ten or more meters across within burial dolomites (Fig. 1A). Burial dolomites are the kilometer-scale volumes of dolostone formed by replacement of limestones by Mg metasomatism at up to 200°C (see Tucker, 2001, p. 148); burial dolomites are called also “hydrothermal dolomites”

(for example, Boni et al., 2000), a term questioned by Machel and Lonnee (2002). Zebra texture can be also found in other rocks as the serpentinite zebra texture shown in Fig. 1B, but we discuss only dolomitic zebra textures in this paper. We also do not refer here to the parallel veins of barite or gypsum that may occur in mudstones (for example, Tucker, 2001, p. 173 and fig 5.9; El-Tabakh and Shreiber, 1998; Machel, 1985).



A dolomitic zebra set consists of up to several tens of parallel disc-shaped veins of dolomite (the so-called dolomite-II, or B, of students of burial dolomitization) that are often remarkably equidistant, even across bedding. The host rock is dolostone, consisting of replacive dolomite, the so-called dolomite-I, or A. The spacing between veins is on the order of 1 cm. Thickness of individual veins is of the same order. Individual veins a few tens of centimeters in diameter may coalesce laterally to yield composite veins up to a meter long. Two veins may merge into one. Each vein typically consists of two halves that leave a seam, visible in Fig. 1A and Fig. 2D, along the center, each half consisting of large euhedral or subhedral saddle-shaped dolomite crystals that are structurally continuous with host wall dolomite crystals and that have grown inward (Tona, 1973; Fig. 2D). Such veins are called syntaxial. In zebra dolomites the set of equidistant veins may cut across the host rock's bedding, which implies that the regularity of spacing cannot be inherited and must therefore originate by some kind of self-organization, as was pointed out by Merino (1984) and Fontboté (1993). But self-organization requires two necessary conditions, disequilibrium and positive feedback (Nicolis and Prigogine, 1977), and neither Merino nor Fontboté could suggest any specific feedback that might account for the observed regularity of spacing.

Zebra textures are also reported that consist of talc (Tornos and Spiro, 2000), fluorite (Zeeh, 1995; Fontboté and Amstutz, 1980), magnesite (Lugli et al., 2000) or sulfide veins (Arne and Kissin, 1989) in Mississippi-Valley-type ores (MVT). In at least the first two of these there is excellent evidence, however, that they are a replacement of an original dolomite zebra vein texture.

Although the main focus here is on the genesis of parallel equidistant dolomitic veins forming rhythmites, we consider also dolomitic breccia textures, which, significantly, may grade into rhythmites (Fontboté 1981; Ovejero et al., 1982). In breccia textures the veins, instead of being parallel, intersect each other, leaving between them blocks of host rock that often would fit puzzle-like if they were brought together.

The consensus today among students of dolomitization and MVT ores is to interpret the veins of both zebras and breccias as passive cement infillings of pre-

FIGURE 1 | **A)** White bilateral dolomite-II veins in black host dolostone-I in a rhythmite from Sierra de Gádor, southern Spain. The two sides of several veins fit well. Transition from host to vein is sharp in hand specimen but gradual under the microscope (as in Fig. 2D). **B)** Zebra serpentine veins in ophiolite of Val d'Aosta, northwestern Italy. Note regular spacing of serpentine veins and very thin veinlets normal to the main veins. The occurrence of these veinlets precludes invoking preexisting open fractures that would have been filled passively by serpentine.

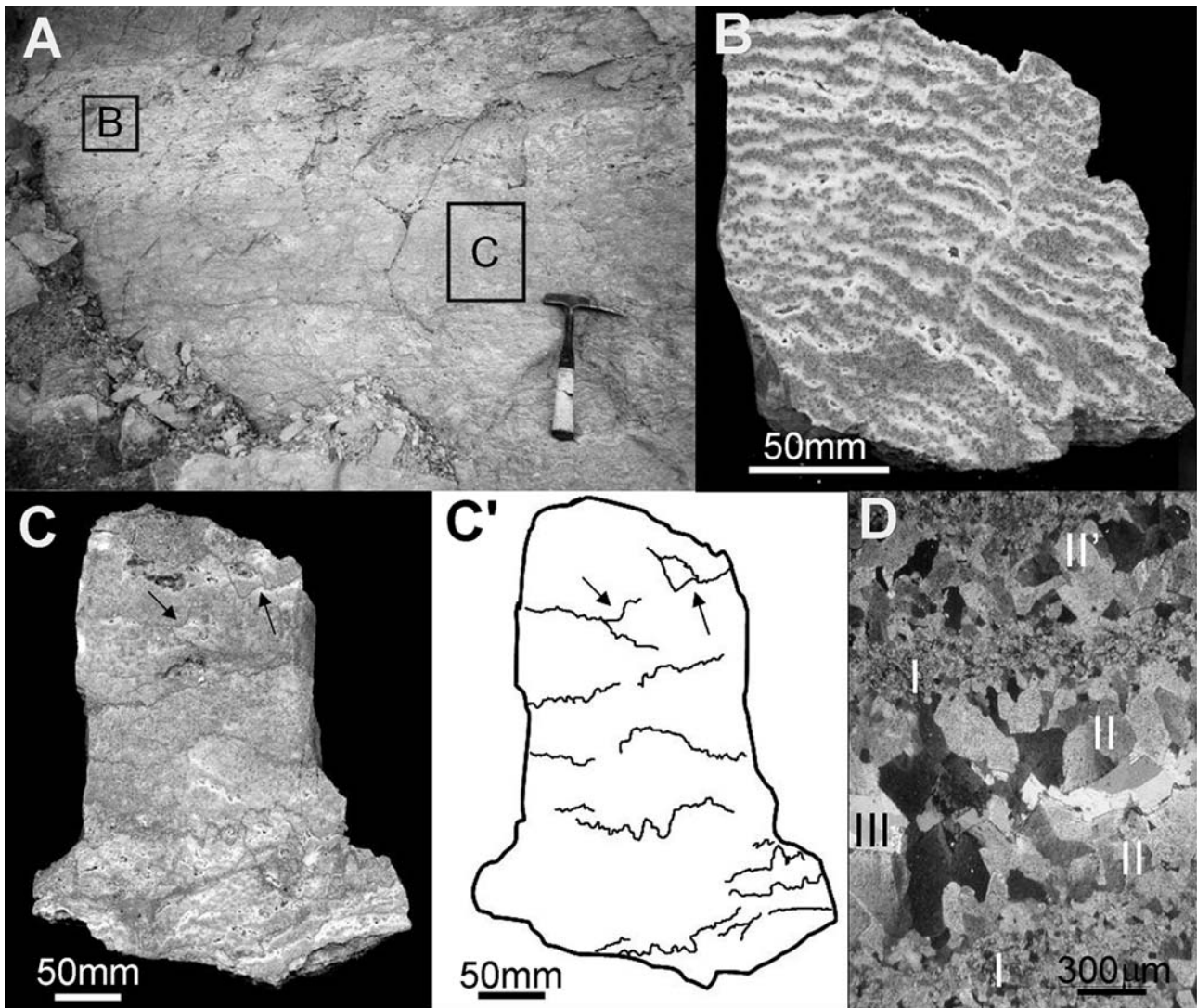


FIGURE 2 | A) Dolomite outcrop at Bueras, Cantabria, northern Spain, showing light colored rhythmite at both upper third (detailed view in B) and bottom third, left of hammer; and gray dolostone I in the center third of photo – see detail in C, faintly showing several small stylolites, sketched in C'. The stylolites in replacive I-dolomite were produced by compression of the center zone caught between the two sets of expanding rhythmites. Several reasons given in the text indicate that the stylolites were contemporaneous with the growth of the white, coarse II-dolomite. Here, the growth of coarse crystals not visible in frame (C) was responsible for the bifurcation of a stylolite at the left arrow in frame (C'), also suggesting simultaneity. D) gradual transition between dolomite of generation I and coarse dolomite of generation II, also reported by others cited in text, suggests that growth of I and II was continuous in space *and time*, thus leaving *no time* for stylolitization (or anything else) to happen in between. This also implies that the stylolites in frames C, and C' were simultaneous with the growth of dolomite II.

existing voids. However, as we explain in the next section, that choice (made in the 80's from only two possible origins, replacement and cementation) was biased from the start because Bathurst (1975) had eliminated from consideration what turns out to be –we believe– the correct origin, namely displacive growth, which had been demonstrated by Taber (1918) and proposed by Folk (1965).

The purpose of this communication is: (a) to show that the veins of zebras and breccias are displacive, that is, they forcibly pushed aside the host dolostone as they grew via the so-called induced stress, the local stress gen-

erated by growth of crystals within a rock; and (b) to propose a specific feedback – one that involves the induced stress – that may account for the self-organization of the veins in zebra textures.

In the following sections we first discuss previous work, then textural evidence for the displacive nature of zebra and breccia veins, then summarize the physics of the recently discovered induced stress (from Fletcher and Merino, 2001), and finally propose a new feedback that could account for the self-organization of zebra veins. In this feedback the induced stress is the “message” between adjacent veins that lets them become regularly spaced.

PREVIOUS WORK

Folk (1965), well aware of both Taber's (1918) demonstration that calcite veins displaced host shales in New York State and Nabarro's (1940) calculation of the elastic energy added to the host by the growth of variously shaped crystal aggregates in it, proposed three types of authigenic carbonate: cements, replacements, and displacive crystals. Similarly, in metamorphic petrology, Turner (in Williams et al., 1954; also in the 1982 edition) showed that porphyroblasts of minerals high in the so-called crystalloblastic series are able to grow idiomorphically against minerals lower in the series, and Misch (1971), Yardley (1974), and Ferguson and Harvey (1980) also proposed that growth of porphyroblasts can displace and deform the schistosity around them by the force of crystallization. However, for carbonates, the influential Bathurst (1975, p. 496), citing Spry (1969) but not Misch (1971) or Williams et al. (1954), ruled out displacive growth as "unlikely" and as doing "needless work". Though these objections had no physicochemical basis, they stuck. Thus Dorward (1985), Horton (1989), Fontboté and Gorzawski (1990), Wallace et al. (1994), Nielsen et al. (1998), and Nelson et al. (1999), faced with interpreting the rhythmic and breccia veins found in burial dolomites and MVT ores, were left with only two of the three possibilities listed by Folk (1965): cements and replacements. Since zebra veins clearly were not replacements, they must be cements. Fontboté and Amstutz (1980, fig. 8b, and p. 304) did show a displacive texture in zebroid MVT ores from southern Spain and described it as produced by the fluorite's crystallization pressure. But Fontboté and Gorzawski (1990) and Fontboté (1993), as noted, later abandoned the idea of forcible displacement and interpreted the zebra veins in burial dolomites and MVT fluorite ores as a cement deposited in dissolution voids. This interpretation has been adopted by other carbonate and ore petrologists (Machel and Lonnee, 2002; Boni et al., 2000; Gasparri et al., 2003; Vandeginste et al., 2005; and many others), who routinely refer to dolomitic zebra veins as cements.

Once zebra dolomite veins had been interpreted as cements filling preexisting voids, the proponents of that view (a) have attempted to find independent evidence of the supposed voids, as well as mechanisms to produce them, (b) have tacitly assumed that all such voids must necessarily get filled with cement, (c) have had to adopt the *ad hoc* criterion that *euhedral* crystals, such as the saddle dolomite-II crystals of the zebra veins, can grow *only* in a preexisting void – a criterion which ignores excellent evidence to the contrary; and (d) have had to invent still

more mechanisms to account for the lack of evidence of the supposed voids. We discuss these problems in turn.

Mechanisms invoked in the literature to produce the supposed voids in the dolostone include hydrofracturing, intraformational fragmentation, microfracturing and focused fluid flow, dissolution, karstification, and desiccation. The very variety of suggestions is unpromising. All these hypotheses are *ad hoc*. No independent evidence is given for any of them. None of them seems able to carve a set of flat parallel voids at once, as would be necessary to make a zebra texture by cementation later. Dissolution is inconsistent with the fact that the two sides of each vein, in both zebras and breccias, often match perfectly (Fig. 1A). It is also always assumed implicitly that the precipitation of vein dolomite must systematically fill a void just because it has been opened. If voids, however made, did exist their walls should be sharp – but this is never the case: characteristically, the transition between the vein's saddle dolomite crystals and the host dolomite crystals is gradational and optically continuous, as noted or photographed by Tona (1973), Fontboté and Amstutz (1980), Horton (1989), Wallace et al. (1994), Gasparri (2003, plates 8 (photo 6) and 9 (photos 1, 3A and 3B)), Roure et al. (2005, fig. 11), Vandeginste et al. (2005), and ourselves (Fig. 2D). To explain the absence of any independent evidence of the postulated dissolution or fracture voids Vandeginste et al. (2005) invoke a new layer of *ad hoc* processes such as "aggradational recrystallization" and "significant recrystallization (Machel, 1997)" which would have destroyed the evidence they needed.

Finally, the criterion generated by dolomitization and MVT ore petrologists to determine that a crystal or crystal aggregate grew as a cement filling a preexisting void – that the crystals must be clear and idiomorphic – is not sufficiently discriminating. For example, the displacive porphyroblasts of Misch (1971) and of Williams et al.'s (1954) crystalloblastic series, and the replacive dolomite from the ore of Galmoy, Ireland, shown in Fig. 3 are all idiomorphic but did not grow in a void.

EVIDENCE FOR DISPLACIVE ORIGIN OF ZEBRA VEINS

Evidence pointing to displacive vein growth in zebra and breccia textures includes (i) stylolites occurring in, or outside of, the rhythmites, and (ii) small transform faults occurring in some veins of breccia and zebra textures.

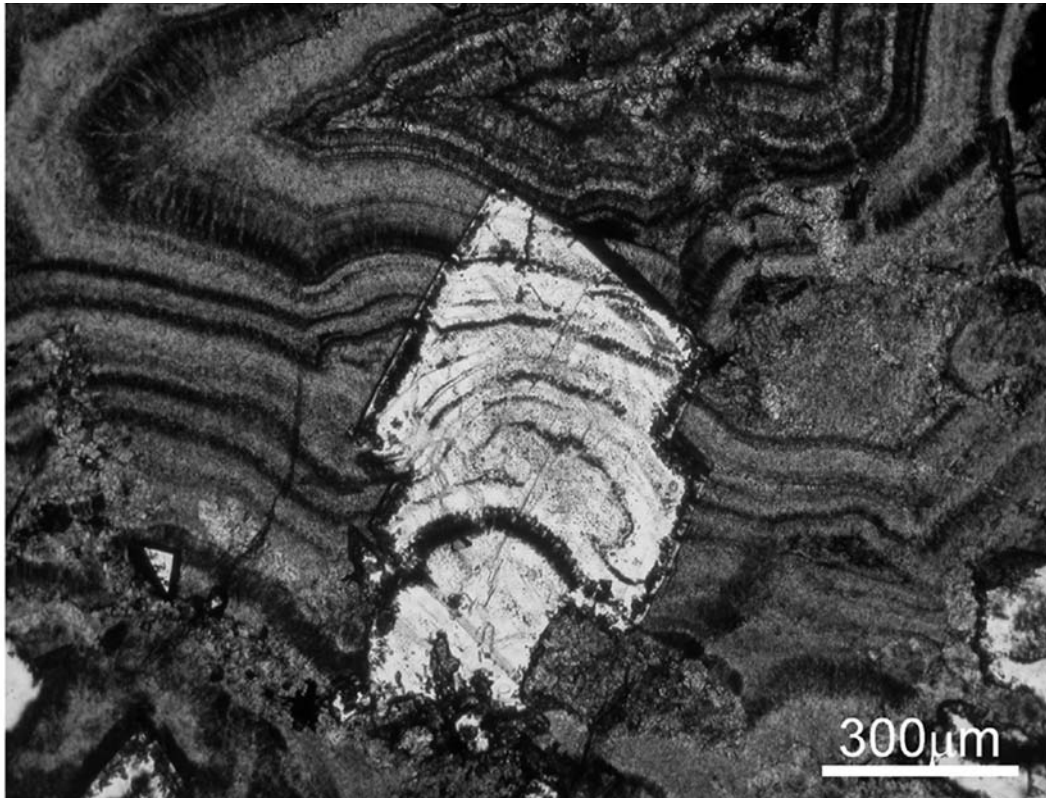


FIGURE 3 | Idiomorphic crystal of dolomite replaces botrioidal sphalerite at Galmoy, Ireland. The dolomite is idiomorphic in spite of the fact it did not grow in a void, as it preserves the morphology of the replaced sphalerite layers. Even if it had grown in a void, the void could not have had the shape of the future idiomorphic dolomite.

Stylolites in Rhythmites

If the dolomite veins of a rhythmite were forcibly displacive as they grew, then the slab of (quite rigid) host dolostone caught between two adjacent veins would be expected to respond to the compression exerted by them by developing a stylolite or two. This is precisely what we have found in the dolostone between adjacent veins and adjacent to rhythmite lenses at a locality near Bueras, Cantabria, northern Spain. The stylolites shown in Fig. 2 are in their spatial distribution and morphology closely associated with small veins, which suggests that they formed as the displacive veins grew precisely in order to compensate for the volume added by the veins, the dissolved material serving as a partial source for further growth of vein dolomite. Many other workers (Tona, 1973; Fontboté and Gorzawski, 1990; Wallace et al., 1994; Nielsen et al., 1998; Swennen et al., 2003; Roure et al., 2005; Vandeginste et al., 2005) have also reported stylolites in the slabs of host dolomite between zebra veins, but have implicitly taken them to be earlier than (and in one case later than), and therefore unrelated to, the formation of the veins. The fact that the stylolites consistently occur just where they are expected if the veins were displacive is good evidence that they were caused by the displacive veins, and that they are therefore simultaneous with the thickening of the veins.

Small “Transform” Faults in Breccias

If initial isolated non-parallel veins displaced the host as they grow, they would break it into blocks, which would fit if brought back together. This puzzle-like fit in a dolomitic breccia can be seen in several areas of Fig. 1, and has been reported by others. Parallel staggered displacive veins such as those shown in Fig. 4 would have to break the slab of host dolostone in between along what we can call a mini-transform fault. This is precisely what the hand specimen of Dunham Dolomite shown in Fig. 5 displays: a small fault between two host rock blocks that starts and ends at the centers of the veins that displaced the two fragments sideways, but does not go beyond the margins of the vein. The same kind of local displacement can be seen in Taber (1918, fig. 3 and others). This feature is characteristic of transform faults, such as the large ones connecting staggered segments of mid-ocean rifts. The occurrence of such occasional mini-transforms in zebras and breccias is excellent evidence that the veins are displacive.

INDUCED STRESS GENERATED BY VEIN GROWTH

The local displacements evidenced by the transform faults and stylolites described in the previous section

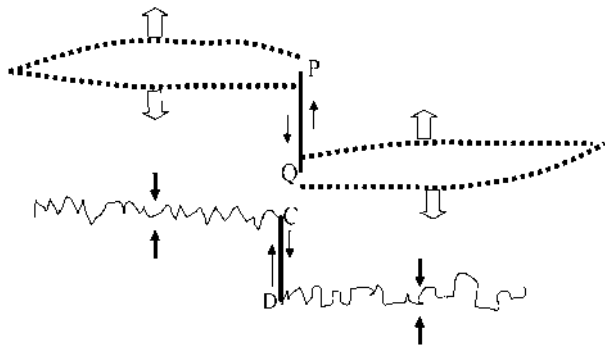


FIGURE 4 | Two en échelon veins that are displacive require a mini-transform fault PQ linking their ends as they grow. One such mini-transform is shown in Fig. 5. The saddle dolomite-II crystals making up each vein grow in structural/optical continuity -see Fig. 2D- with dolomite crystals of the host (this is why these veins are called *syn-taxial*) and grow inward, leaving a seam in the center, visible in Fig. 1A. Hollow arrows indicate direction of thickening of the veins. Thick solid arrows indicate direction of host rock movement with respect to a stylolite. The thin arrows indicate relative sense of displacement on each mini-transform fault. The growing displacive veins exert an induced stress that is predicted to drive simultaneous formation of stylolites parallel to the veins as observed. Two en échelon stylolites also require a mini-transform fault CD linking their ends, to allow consumption of host rock by pressure solution.”

must be driven by a local stress. This stress is the induced stress generated by the growth of zebra and breccia veins. The induced stress – a term borrowed from Carmichael (1986) – is only loosely related to the empirical force of crystallization of Becker and Day (1916) or to the force of crystallization calculated by Ramberg (1952, p. 15). It differs from the force of crystallization in that it depends, conceptually and quantitatively, on the kind of mechanical constraint exerted by the host rock on the crystal growth taking place within it.

Physics of the induced stress

Growth of a crystal or crystal aggregate in a rock, other than in a pore or cavity, necessarily generates a local stress. Fletcher and Merino (2001) calculated its magnitude in three cases, one of them displacive veins, by coupling the new mineral’s growth kinetics with whichever rheological or mechano-chemical behavior the host rock responds to that growth. Displacement driven by crystallization force (or, as we rename it, by the induced stress) was shown by Taber (1918) and Misch (1971). Walder and Hallet (1985) gave a sophisticated quantitative treatment of the displacement caused by ice wedges in soil. Maliva (1989) described syntaxial displacive calcite. Maliva and Siever (1988) proposed the fundamental new idea that a mineral replacement happens not because the host mineral dissolves first and somehow pulls behind itself the precipitation of the new, as is conventionally thought, but because the new mineral grows and, via the induced stress it generates, pressure-dissolves the host mineral. In short, the three basic responses of the host to crystal growth, and to the induced stress generated by it, are pressure-solution, displacement, and fracturing (see fig. 8 in Fletcher and Merino, 2001).

Vein-shaped growth

The shape of the aggregate of new crystals (or the shape of the new single crystal) is an important factor in determining, and interacting with, the induced stress field. Nabarro (1940) compared the elastic energy injected into the host plus guest growth system by mineral growth (per unit volume of new mineral) for disc-shaped, spherical, and cigar-shaped crystal aggregates. A vein-shaped aggregate turns out to “inject” the least elastic energy into the



FIGURE 5 | Dolomitic breccia in the Cambrian Dunham Dolomite of NW Vermont and southern Quebec. The two black blocks of host rock at center were differentially displaced along an east-west fault $t-t'$, dashed, that starts and ends at the centers of the veins but that does not affect the walls. This means that $t-t'$ is a transform fault, and requires that the observed displacement of the blocks relative to each other was forcibly driven by the white veins as they grew.

host plus guest system, and is therefore theoretically preferred from an energetic point of view to the other two aggregate shapes. But vein-shaped growth requires (a) sufficient supersaturation to drive displacement of the walls against the host and (b) an incipient flaw size sufficient to initiate fracture propagation at the tips of the vein. If this requirement were not satisfied, a crystal growth aggregate would adopt spherical, ellipsoidal, or cylindrical shapes, instead of vein shape.

Models of zebra and breccia sets of veins

We model the bodies of zebra and breccia textures in burial dolomites as sets of many uniformly dispersed, incipient, disc-shaped veins of radius c and width w that grow within a roughly spherical “mineralized zone” 1 to 10 m in size; a small portion of this mineralized region is shown in Figs. 6A and 6B. To visualize the volume fraction of veins, f , each is supposed enclosed in a representative volume element (RVE) of radius $b \geq 2c$, so that $f = (c^2w)/(2b^3) \ll 1$, since for a vein $w/c \ll 1$. The induced stress at a distance r from the vein is proportional to the cube of the c/r ratio (Fletcher and Merino, 2001, eqs. 10 and 12), which means that it declines very fast with distance away from the vein; this is why the induced stress is always a local stress. The RVE thus qualitatively represents the “halo” of induced stress generated by the vein growth inside it.

Where the host mineralized zone is subjected to slightly unequal principal stresses, the incipient veins all grow normal to the least principal stress (Fig. 6B), leading to the development of a rhythmite. Alternatively, equal principal stresses should promote nucleation and growth of randomly-oriented veins (Fig. 6A). Upon growth these ran-

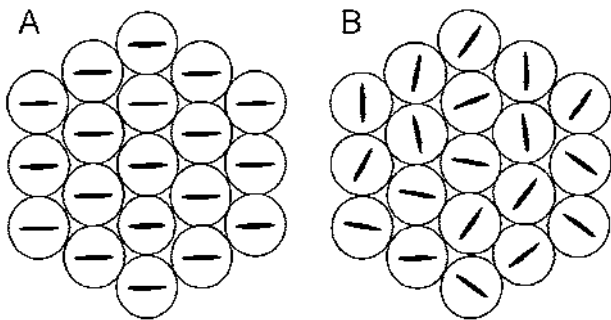


FIGURE 6 | Schematic diagrams of parts of the central section of a spherical mineralized zone containing parallel veins, (A), and uniformly dispersed randomly oriented veins, (B). The randomly-oriented veins are artificially pictured all lying normal to the plane of the figure. Since the radius of a sphere enclosing a disc vein is about twice the vein radius, the induced stress at its surface will be $\sim (1/2)^2$ the maximum value, and further vein growth will involve significant mechanical interaction. For unequal principal stresses the incipient veins start out growing all normal to the least compressive stress, leading upon further growth and *triage* (Figs. 7 and 8) to a rhythmite.

dom veins would intersect and become connected, producing a breccia texture. The expansion of the veins in the spherical mineralized zone is supposed compensated by pressure solution of the surrounding host rock, and/or of the intervening host rock, at stylolites that develop simultaneously with the vein growth. The host rock within the mineralized zone does not flow, but expands elastically in response to vein propagation and widening.

Induced stress generated by a vein

Following the derivation in Fletcher and Merino (2001, eqs. 27a and 28) the normal induced stress σ_{nn} exerted outside the mineralized zone and the growth rate of each vein are respectively

$$\sigma_{nn} = [S + (MRT/V_A)\ln\Omega]/(1+M) \quad (1)$$

and

$$dw/dt = 2k_A[RT\ln\Omega - SV_A]/(1+M), \quad (2)$$

where t is time, S is minimum tensile stress required for crack propagation ($S \sim 0$ for intersecting veins as in breccias and ~ 5 MPa for rhythmite veins; see Table 1), k_A and V_A are growth rate constant and specific volume of mineral A, here dolomite; Ω is the local pore-fluid supersaturation with respect to dolomite, R is the gas constant, and T is absolute temperature. The rate constant k_A (in s/cm) is consistent with a rate law of the type

$$G = k \Delta\mu \quad (3)$$

where G is the linear growth rate in cm/second and $\Delta\mu$ is the supersaturation in chemical potential units, energy/mass, equivalent to velocity squared; see Table 1. The dimensionless quantity

$$M = (16/3)\eta k_A V_A (c^2/b^3) \quad (4)$$

includes the radius, b , of the representative volume element or halo of induced stress, dashed in Fig. 7; the radius c of the incipient vein; and the viscosity, η , of the host rock.

Equation (1) indicates that the normal induced stress exerted by a growing vein on its host-rock walls increases with the log of the supersaturation driving the growth, and varies with the factor M , essentially proportional to the product ηk_A of host viscosity times the growth rate constant of the vein mineral, A.

Numerical application

For example, an incipient displacive dolomite vein $c = 0.2$ cm in radius in a sphere of radius $b = 1$ cm,

TABLE 1 | Table of Symbols.

| | |
|---------------|---|
| <i>c</i> | radius of a disc-shaped vein |
| <i>b</i> | radius of sphere of host rock containing a disc-shaped vein; $b > c$ |
| <i>f</i> | volume fraction of a vein |
| <i>G</i> | Growth rate of the new mineral in $\text{cm}^3/\text{cm}^2 \text{ second} = \text{cm/s}$, eq 3. |
| k_A | Rate constant of growing mineral (A, dolomite I and II), consistent with a linear rate law of the form $G = k\Delta\mu$, (eq 3). Values of <i>k</i> in s/cm for several minerals were derived (in Fletcher and Merino, 2001, table 2) from published experimental values in mole/cm ² s. We take $k_{\text{dolomite}} = 10^{-17}$ s/cm, one-tenth of the rate constant for calcite. |
| <i>M</i> | a parameter defined as $(16/3)\eta k_A V_A (c^2/b^3)$, eq 4 |
| <i>R</i> | Gas constant, 8.31 J/mole K |
| <i>r</i> | distance from vein |
| <i>S</i> | minimum tensile stress required for vein-crack propagation, taken equal to zero if the veins intersect (as in breccia texture); and taken equal to 5 MPa for non-intersecting veins in a zebra texture |
| <i>T</i> | absolute temperature (in burial dolomitization between 60 and 200° C) |
| V_A | specific volume of growing mineral, about 1/3 cm ³ /g and 64 cm ³ /mole for dolomite |
| <i>t</i> | time |
| <i>w</i> | vein thickness |
| σ_{mn} | normal stress exerted by a displacive vein on its walls; eq (1) |
| $\Delta\mu$ | thermodynamic affinity for growth of mineral A (equal to $RT\ln\Omega$), in chemical potential units of ergs/gram = (cm/second) ² |
| Ω | saturation of local pore fluid with respect to the mineral of interest, equal to Ion Activity Product / Equilibrium Const. |
| η | rock viscosity, in Pascal x second (= 10 g/cm s). Dolostone viscosity used in the text is 10^{16} to 10^{18} Pa s, one to three orders of magnitude greater than the viscosity of Yule marble in Clark (1966, p. 289). |

TABLE 2 | Summary of results of calculations based on eqs 1-4

| Viscosity, poise (= g/cm s) | 10^{17} | 10^{18} | 10^{19} |
|---|--------------------|--------------------|--------------------|
| <i>M</i> , eq 3 | 0.064 | 0.64 | 6.4 |
| Induced Stress on host walls, MPa, eq 1 | 8 | 24 | 47 |
| Vein growth rate, cm/s, eq 2 | 6×10^{-7} | 4×10^{-7} | 9×10^{-8} |
| or in cm/month | 1.5 | 1 | 1/4 |

growing at 100°C (373°K) under a moderate supersaturation of $\Omega = 3$ in a burial dolomite, with a dolomite growth-rate constant of $k = 10^{-17}$ s/cm (estimated here as 1/10 of the calcite rate constant given in Fletcher and Merino, 2001; Table 2), and a supposed dolomite viscosity of 10^{16} to 10^{18} Pa s (that is, one to three orders of magnitude greater than the viscosity of Yule marble at 400°C and normal to foliation, Clark, 1966, p. 289), with other values in Table 2, would according to equation (1) exert an induced stress of ~ 8 to 47 MPa, or 80 to 470 bars, and according to equation (2) lead to a vein wall displacement rate of $\sim 4 \times 10^{-7}$ cm/s, equivalent to about 1 cm per month. It follows that a body of zebra dolomite veins 1 cm thick each would form in one month too. While this growth rate seems geologically fast, it is fully consistent with a self-accelerating dolomitization feedback we have discovered in unpublished work in progress (Merino, 2006).

SELF-ORGANIZED RHYTHMITES: A CHEMICAL / MECHANICAL FEEDBACK

The second problem posed in the Introduction was: How do the parallel veins of a dolomitic zebra texture turn out to be so regularly spaced, even where they cut across the bedding of the original limestone? Zebra textures were identified as a case of geochemical self-organization (Merino, 1984; Fontboté, 1993), that is, a case where the system acquires a regular textural pattern out of its own dynamics, not by inheritance. Every case of self-organization requires disequilibrium and a specific positive feedback (Merino, 1984; Ortoleva et al., 1987). Recent attempts by Nielsen et al. (1998), Swennen et al. (2003) and Vandeginste et al. (2005) at understanding the genesis of zebra textures neglect considering those requirements of self-organization, and do little more than hypothesize an origin of zebra textures by formation of “extensional microfractures or cavities,” or by hydrofracturing, or by “focalized fluid expulsion,” or by

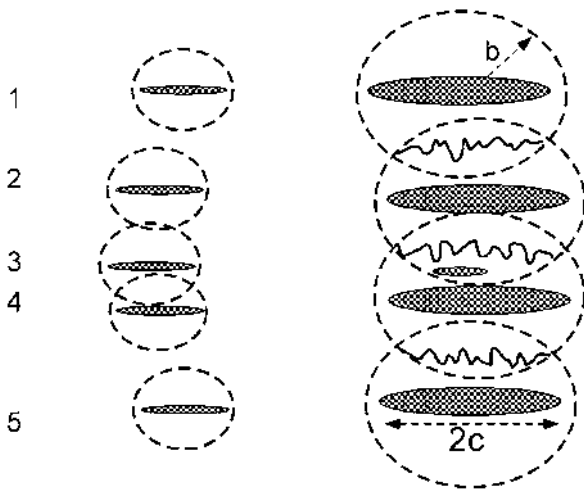


FIGURE 7 | Genesis of stylolites between veins, and *trriage* of veins of generation II, via the induced stress. Left: a set of randomly spaced incipient veins, each with its (dashed) sphere of influence of the induced stress it generates as it grows. Right, same set of veins after further growth. Now the dashed spheres of influence are larger (their size is proportional to $(c/r)^2$) and overlap: stylolites could arise in the extra-stressed overlap volumes, as shown. In addition, vein #3, which was from the start too close to vein #4, now finds itself within the overlap volume of both veins #2 and 4; the sum of induced stresses in the overlapping volume has stunted it and has started to pressure dissolve it. The veins surviving this *trriage* are now more regularly spaced than before, accounting for the strikingly regular spacing of rhythmites. See proposed feedback in Fig. 8.

“suprahydrostatic pressures generated in a compressive stress regime.” No independent evidence is presented of any of these *ad hoc* hypotheses or of how they would produce equidistant mineral veins. As discussed above, no evidence is presented of the existence of any prior voids either.

Only now, after the induced stress generated by growth in rocks has been conceptually established and

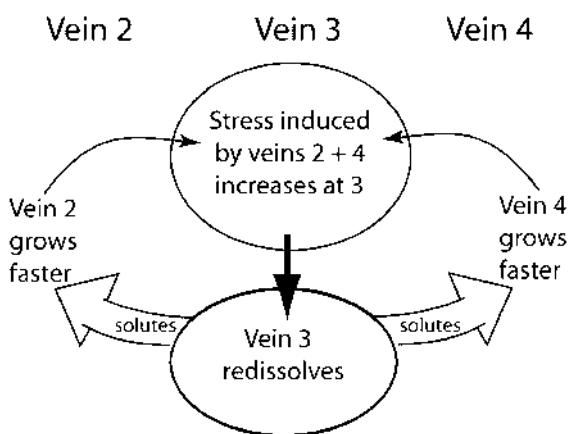


FIGURE 8 | *Triage* feedback proposed, keyed to the veins of Fig. 7: vein #2 at left, #3 at center, #4 at right. Growth of both #2 and 4 exerts an induced stress on #3. Vein #3 stops growing and redissolves, releases its ions, and these diffuse back to 2 and 4 and help make them grow even faster and exert even greater stress on #3.

quantified, has it become possible to find a specific feedback that might account for the self-organization involved in rhythmites. The feedback is as follows.

As shown in Fig. 7, a growing vein exerts a local induced stress on the host rock, with the magnitude of stress decaying away from the vein as $\sim (c/r)^3$, where c is the radius of the disc-shaped vein and r is distance from the vein. Of a set of numerous incipient parallel veins at random spacings, some of the veins (those that happen to be very close to their neighbors, such as vein #3 in Fig. 7) would soon find themselves within their neighbors’ halos of induced compression, where r is $< 2c$, and thus would soon become pressure-dissolved, the redissolved material serving as a partial source of solutes for further growth of the surviving veins, closing the feedback loop (Fig. 7). The surviving veins, such as veins 2 and 4 in Fig. 8, would be more regularly spaced than before. Continuity-based modeling of this feedback is still necessary to confirm or refute that it can indeed produce a zebra texture with spacings of the observed order of magnitude.

The *trriage* of veins described above is similar to that shown earlier (Merino, 1992) to explain the regular spacing of stylolites in that it also involves a spontaneous selective removal, a “thinning,” a “weeding,” of those incipient veins that happen to be initially too close to their neighbors. The difference is that in rhythmites the *trriage* takes place *via* the induced stress generated by displacive veins, whereas in stylolitization the *trriage* takes place by a porosity or microporosity feedback.

CONCLUDING REMARKS

The basic conclusion here is that dolomitic zebra and breccia veins are displacive veins, that is, veins that forcibly make room for themselves as they grow. These veins do not need a preexisting open space to grow into. The stress necessary to drive those local displacements is none other than the induced stress calculated in Table 2 from eqs 1-4. The induced stress is the properly conceptualized version of the empirical force of crystallization of Becker and Day (1916). The main difference is that the induced stress depends fundamentally not only on the kinetics of growth of the new mineral but on the kind of mechanical or mechano-chemical response and properties of the host as well.

Displacive veins, in making room for themselves forcibly, are predicted to pressure-dissolve the (mechanically rigid) host dolomite in the form of stylolites parallel/subparallel to the veins. Pressure-solution of host rock at these stylolites tends to compensate for the increase of volume represented by the veins. The fact that the stylolites do occur right where they are expected to form if the

veins were displacive is evidence (a) that the veins are displacive, and (b) that the stylolites form *simultaneously* with the displacive vein growth.

In addition, the induced stress, because it is local, enters into a feedback with the local mineral kinetics that can selectively eliminate incipient veins that happen to form too close to their neighbors. This would explain well why the veins are so strikingly equidistant, just as a similar “weeding” feedback, or *triage*, explained why stylolites of a set tend to become fairly equidistant as well (Merino et al., 1983; Merino, 1992).

All the difficulties met by other authors in explaining the genesis of zebra textures seem to us to arise from the *a priori* acceptance of the idea that veins must be cements. Cements need a prior void, and the prior void needs a process to make it, and those processes need driving forces, and have other consequences. There is no independent evidence, however, of either the voids or the processes invoked to make them or their driving forces. The zebra and breccia veins are simply not cements. On the other hand, if the veins are regarded as displacive (and we present good evidence of displacement driven by their growth), and with the help of the induced stress concept, everything falls into place. The displacive veins consist of crystals that grow syntaxially on replacive dolomite crystals of the host. Why the growth spontaneously and gradually passes from replacive to displacive - and then stops when the displacive veins are on the order of 1 cm thick - is accounted for by the self-accelerating dolomite-for-calcite replacement (Merino, 2006), and its effect on the rheology of dolostone, which is strain-rate-softening.

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