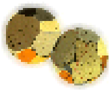

Domain boundary migration at multiple scales in experiment and nature

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Introduction

The link between deformation process and resulting microstructure is fundamental to our ability to correctly interpret and quantify the products of deformation and metamorphism on the grain scale. The present study was triggered by our observation that domain boundary migration could be documented over a range of scales from (10 µm up to 10^{12} µm), prompting us to raise the question as to whether the underlying processes could be of a fractal nature. One successful approach that has been taken in the past to establish the links between process and microstructure has been the use of analogue modelling techniques (see Means 1989 and references therein). One of the keys to the successful application of the results of analogue modelling is to be able to demonstrate that the various processes can be accurately scaled with respect to nature. In this paper we also take an analogue approach, and we believe that we can successfully scale the microstructures seen in naturally deformed rocks by simultaneously

increasing the length scale (up to $2\cdot10^{13}$ µm) while decreasing the time scale, although it is to our advantage that the time scales used are several orders of magnitude longer than classical analogue experiments (up to $3\cdot10^{9}$ s). The accumulated data and observations warrant a 'historical' review of micro-scale processes.

At the end of the day, and as we draw close to the end of the millennium, it is the ability of the analogue technique to accurately reproduce natural microstructures that provides the strongest justification for this form of work, and we are lucky that we can borrow from a significant body of previous work in finding appropriate results (Centennia 1996, Kinder & Hilgemann 1978,1995). In this poster we present a set of examples from our studies that suggest the methodology we have established holds significant promise for future discoveries. At the same time, it is a salutary lesson that even given a plethora of examples, there is still some ambiguity that needs to be resolved.

1. Domain Boundary Migration and Grain Geometries

Using time lapse imaging techniques, we are able to document the evolution of domain sizes through time in our study area (Fig 1 & 2). It is apparent that there is a progressive gradual domain size reduction until the last stages of the experiment, at which time the domain size becomes even larger than its initial state. We consider this to be a classic example of grain size reduction by a rotation recrystallisation mechanism, followed by meta-dynamic grain boundary migration (Urai *et al.* 1986). Throughout this sequence, domain shapes are relatively equant, except in a few rare and short-lived examples (Fig 3), and this tends to suggest that there is a significant surface energy term which prevents high surface area to volume domains from remaining stable. Given this strong surface energy, and the impact of global warming, we predict that a foam texture will develop in the study area. Based on an extrapolation from measured domain sizes (Fig 2) and numerical simulations (Bons & Urai 1992), we are able to present a prediction as to what this future state(s) will look like at about $t=6.5\cdot10^{10}$ s (Fig 2d), and we await the validation of our predictions with some trepidation.

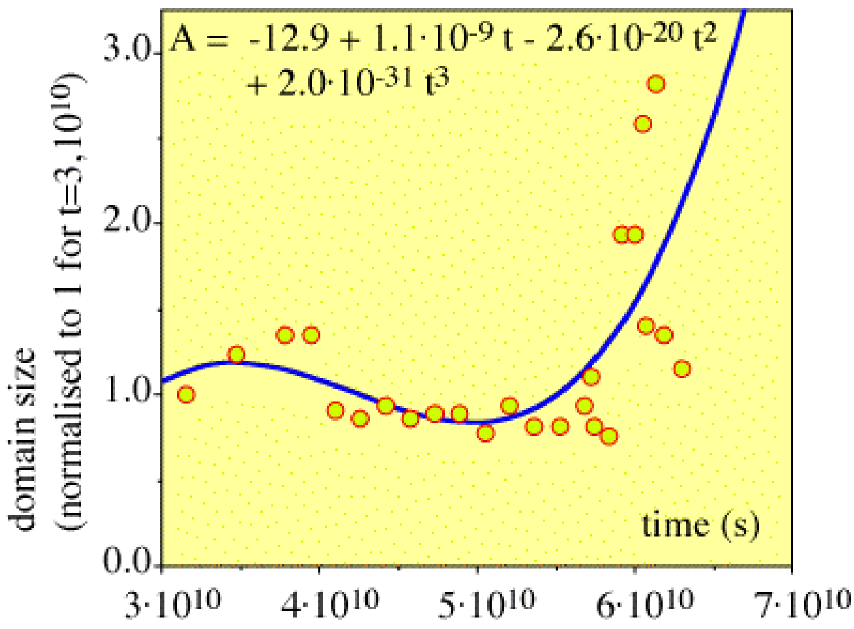


Figure 1. Graph showing the mean domain size (A) as a function of time (t). The domain size is normalised to $t=3\cdot10^{10}$. Although the scatter in the data increases towards the end of the experiment, there seems to be a general underlying trend towards larger domain sizes after $t=5.5\cdot10^{10}$. The data give a reasonable fit to a third-order polynomial, predicting an increase in domain size in the near future. Domain sizes were measured using the image processing package "NIH-Image" for Macintosh (see caption figure 2).

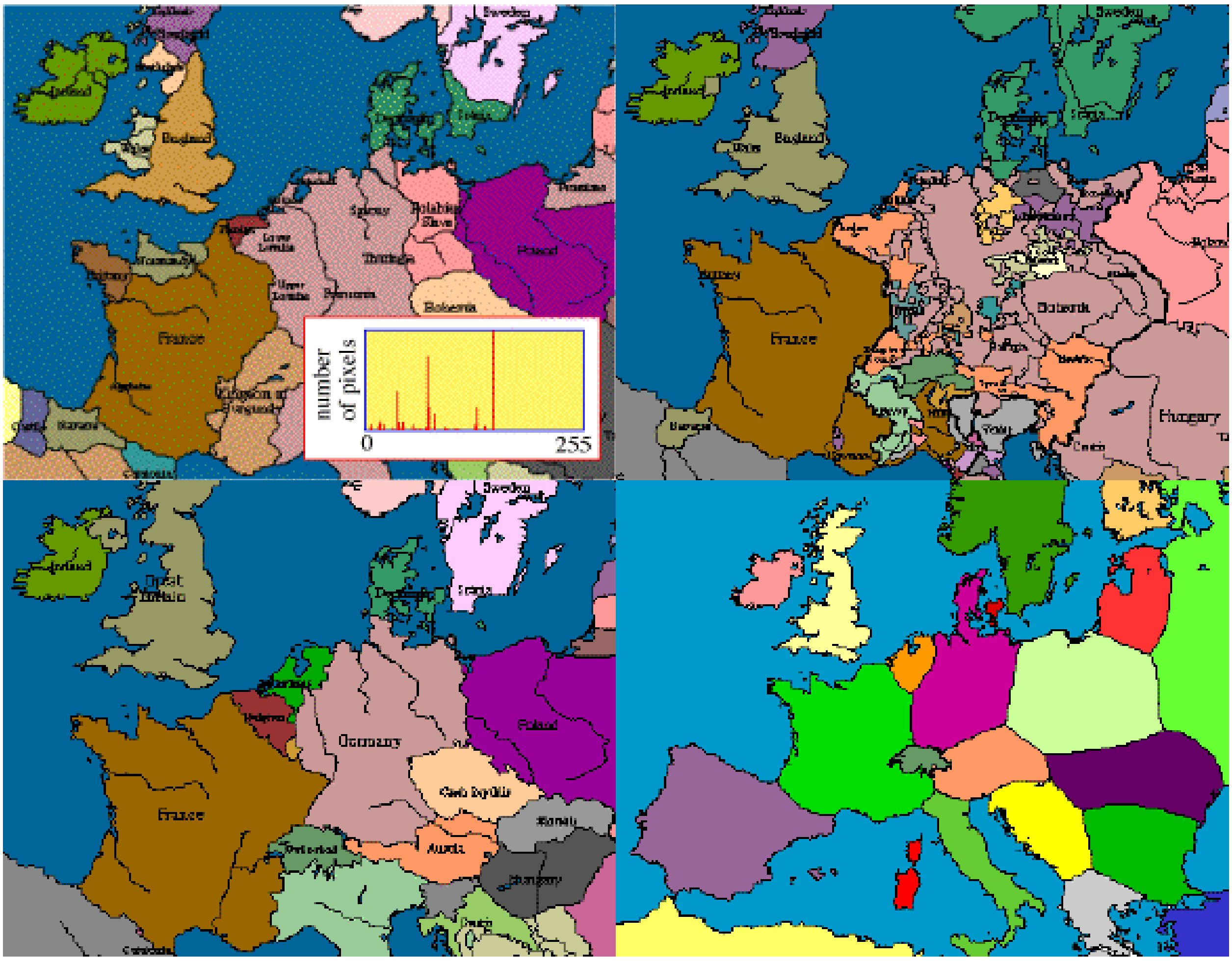


Figure 2. False-colour maps of central and western Europe at (a) $t=3.156\cdot10^{10}$, (b) $4.734\cdot10^{10}$ and (c) $6.296\cdot10^{10}$ s, based on CENTENNIA data. Each political domain is represented by one colour. Notice that one domain can occupy disconnected regions (for instance the orange coloured Habsburg estates, scattered from the Adriatic to the North Sea in figure b). Domains were analysed using state-of-the-art image analysis techniques (Bons & Jessell 1996). In this particular case, a histogram (inset in figure a) of the frequency of pixel values (each representing one colour and hence one domain) was constructed with the package NIH-IMAGE. The number of peaks (minus two for boundaries - black - and sea - blue) is the number of political domains. (d) Prediction of the foam-type domain topology at about $6.5\text{-}7.0\cdot10^{10}$ s, based on the observed trend and numerical modelling, taking into account the expected effects of

global warming. Notice that Switzerland is protected by the pinning behaviour of the large topographic highs (See Box 2).

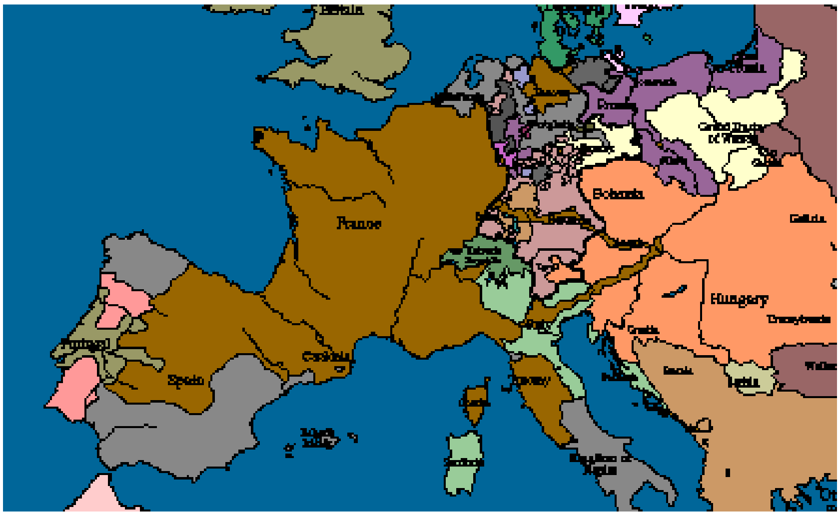


Figure 3. Napoleon quickly moved from Spain, where he was campaigning, to Austria in the "Fifth War of the Coalition". He marched deep into Austrian territory until after the Battle of Wagram the Peace of Schànbrunn was signed. The peace led to a rearrangement of the national boundaries to a more stable configuration than shown here. The new arrangement however quickly proved to be metastable and eventually unstable. ($t=7.70877\cdot10^{10}$)

2 Pinning Microstructures

In principle the grain size in a deforming aggregate can be used as an indicator of the flow stress (Twiss 1986, Poirier 1985). Unfortunately in many rocks there is a strong mediating influence on grain size provided by the volume and distribution of secondary phases, which prevents equilibrium grain sizes from being reached through the second phases' ability to act as pinning particles on grain boundaries through Zener drag. When the distribution of these particles in a region is irregular, this may lead to the local development of highly stable grain boundary configurations, even during periods of intense domain boundary migration in other parts of the material (Fig 4).

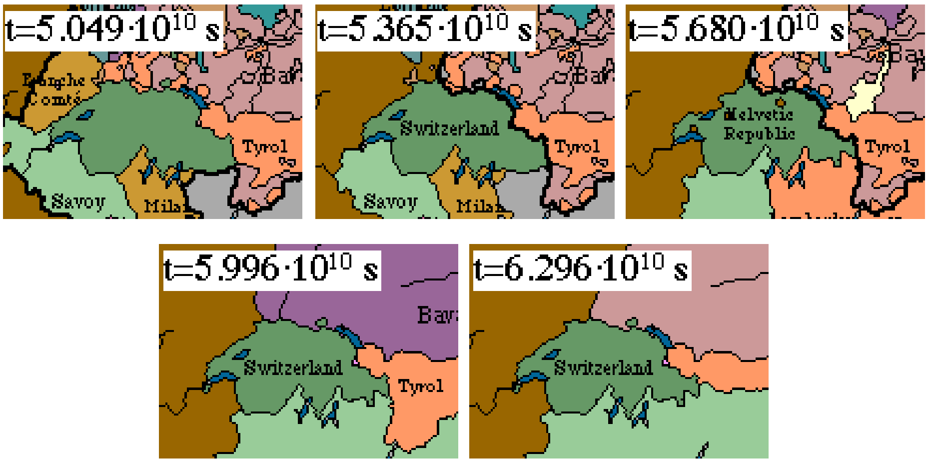


Figure 4. The 3 original cantons joined in the "Eternal Union" in 1291. The confederation then expanded and acquired more cantons, mostly at the expense of the Habsburgs in the Holy Roman Empire. After a couple of battles, the Swiss gained political independence from the empire at the Treaty of Basle in 1499 ($t=4.730\cdot10^{10}$ s) and expanded to a confederation of 13 cantons. Since then nothing much happened in "Switzerland" (with the exception of John Calvin fleeing to Basle and writing his "Institutio Religionis Christianae" there and we can see that from $t=5.049\cdot10^{10}$ s onwards, the boundaries of the Swiss domain remain essentially unchanged, while around it things change rapidly. The lakes and mountains appear to act as classical boundary-pinning agents.

3 Grain Migration

The phenomenon of Grain Migration, first documented by Means (1983), demonstrates the concept of the grain as an orientation domain boundary. Grain Migration can occur when the local driving forces for grain boundary migration are such that diametrically opposite boundaries of a grain migrate in the same direction. In this case the centroid of the grain may eventually shift beyond the original boundaries of the grain, and no material from the initial grain is present in the final grain (Fig 5). It has been proposed that this may represent a significant material transport mechanism if particles in the domain boundary are swept along with the grain (Ashby & Centamore 1968), and there is a uniform migration of many grains through the area.

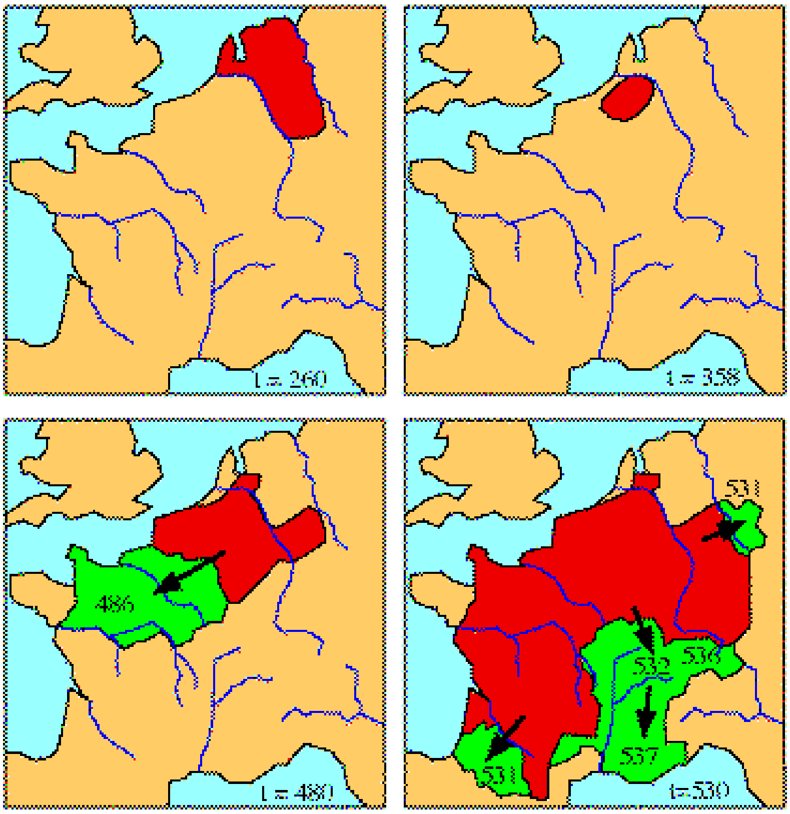
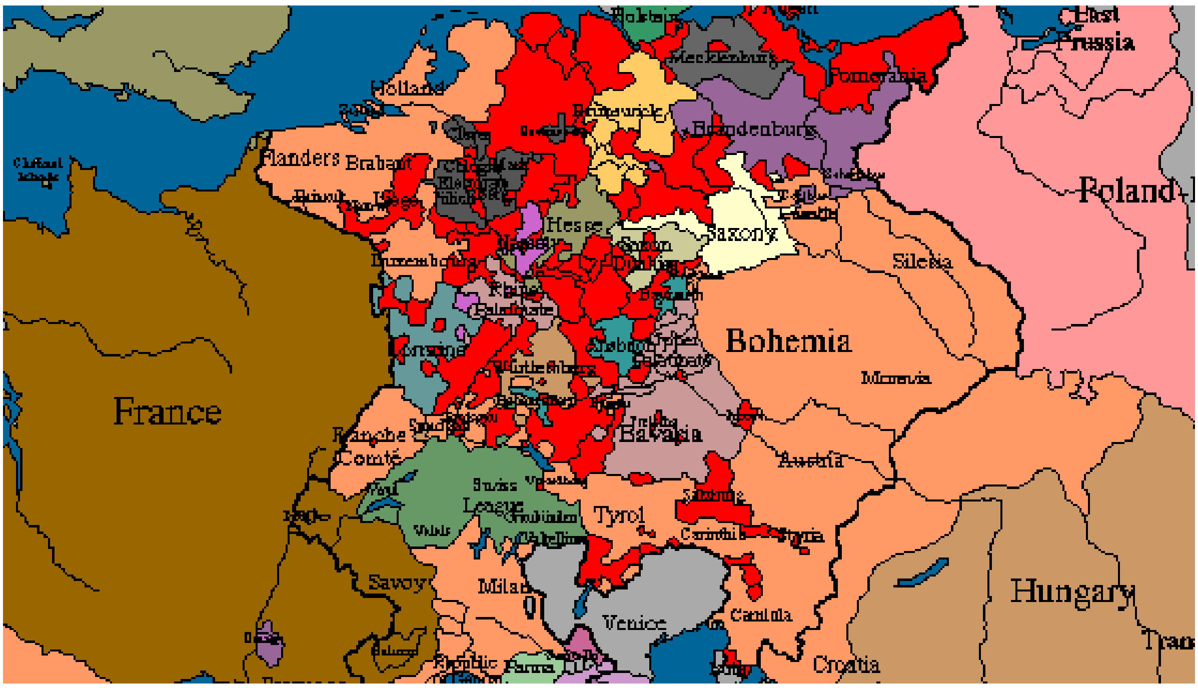


Figure 5. The tribal settlement of the Franks between 260 and 537 saw them expand slowly from the border of the Rhine to the south and west. By 480 they occupied lands almost totally unrelated to their original holdings, although by 537 there was again some overlap with the original boundaries of their lands. The driving force for their migrations have not been recorded, however if we apply the principle of uniformitarianism it seems probable that it had something to do with the weather.

4 Orientation Families

The recognition of orientation families (isolated identically oriented grains formed as a result of grain bisection by grain boundary migration; Urai 1983) has proved to be a key indicator of significant grain boundary migration in naturally deformed rocks (Fig 6a). Nevertheless, within a specific field of view care must be taken to ensure that the apparently isolated grains are not in fact connected in the third dimension. Such extra-dimensional links are reminiscent of the "worm-holes" in physics. Two examples are given in Fig 6b.



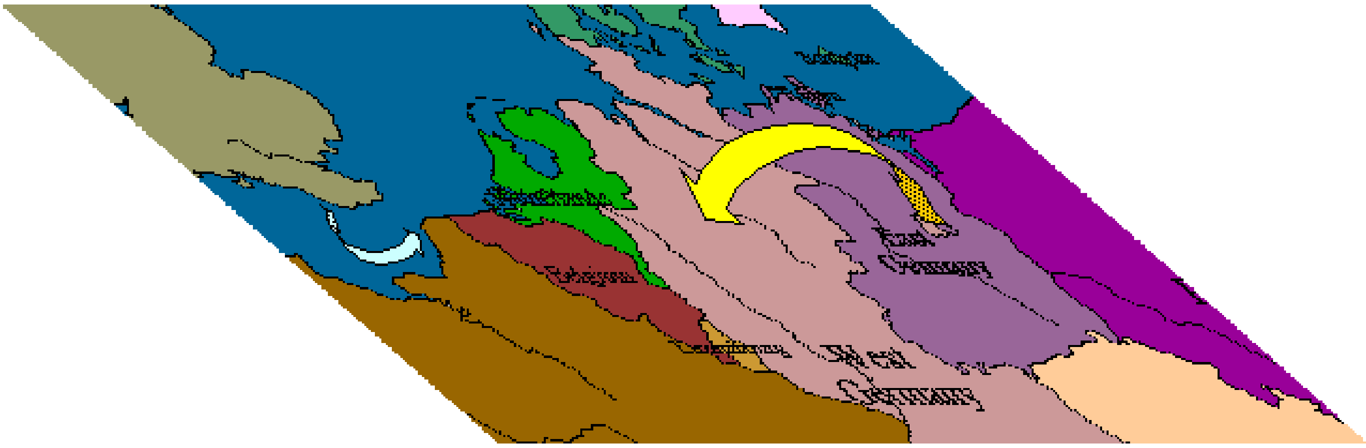


Figure 6. (a) The German empire at the end of the Middle Ages was composed of numerous territories. Many of these territories belonged to a few rulers or formed other political unions. The example here shows the situation at 1550 ($t=4.891 \cdot 10^{10}$ s) when the Lutheran Scmalkaldic League and the Catholic Habsburg Empire both formed political units composed of many disconnected regions. **(b)** In the 20th century, few disconnected regions belonging to a single political unit remained, with the notable exception of West Berlin. The 2-dimensional map-view may however be misleading as Berlin and West Germany were connected by the famous air-bridge (yellow arrow) in the third dimension, even when all other connections were cut-off in 1948-1949. Another "extra-dimensional worm-hole" appeared later between two politically and culinary different units: France and Britain (blue arrow). We anxiously await the effect of this new link.

5 Lattice Control of Sub-grain Structure

In situations where a migrating reaction front passes quickly over an area, it is commonly observed that the sub-structure behind the front bears no relation to the previous state (we will call this Type I behaviour, Fig 7). In contrast it appears that during slow movement of the front, the sub-grain structure may be lattice controlled (Type II). We dismiss as pseudo-science a colleagues' suggestion that the formation of Type II boundaries could in any way be related to the observation that they are parallel and normal to an external geographic reference.

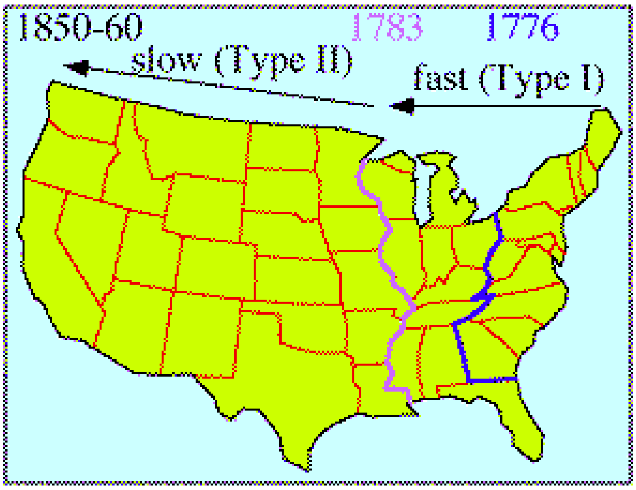


Figure 7. Expansion of British colonies on the east coast of North America was initially hindered by a prohibition on settlement west of the Appalachians. Conflict between the settlers and the British motherland (apparently centered around how to brew tea) lead to the independence of the colonies. This opened up the North West Territory which was quickly divided up in several states. The $15 million dollar Louisiana purchase from Napoleon enabled further westward expansion, leading to complete white settlement up to the west coast. The west-coast states were established around 1850-1860. The much slower migration on the western half of the continent is reflected in much more regular and straight state boundaries than in the east.

6 Defect Energy Driven Fluid Assisted Diffusive Mass Transfer

Although chemical energy is generally the largest driving force for Diffusive Mass Transfer (DMT, Urai et al 1986), in certain circumstances the presence of high densities of defects, i.e. Defect Energy Driven Diffusive Mass Transfer (DEDDMT) in a grain have been shown to result in the DMT over length scales equivalent to many grain diameters. In the example shown the transport mechanism was clearly fluid assisted (Fig 8) i.e. Defect Energy Driven Fluid Assisted Diffusive Mass Transfer (DEDFADMT), although there is some evidence that a previous episode of DEDDMT to the same domain was achieved largely via a self-diffusion mechanism through the solid i.e. Defect Energy Driven Solid State Diffusive Mass Transfer (DEDSSDMT). It is strikingly apparent how closely related

DEDDMT is to Co-Operative Near Volatile Induced Cation Transport (CONVICT).

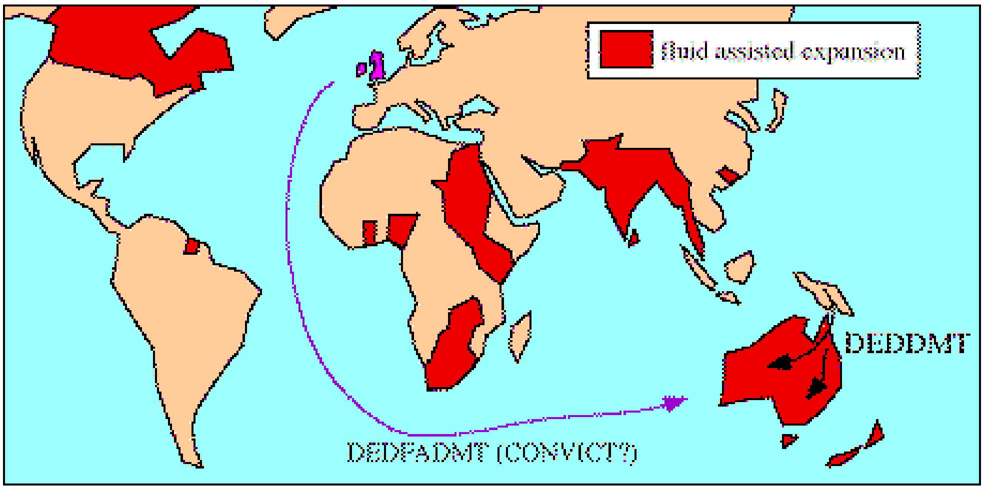


Figure 8. The Australian continent was a Terra Nullius about 30-50,000 BC, when first settlement occurred by people who walked over from New Guinea, (DEDSSDMT). In 1788 the country was invaded by British settlers and convicts. They used the sea as a very efficient transport medium (DEDFADMT). Later events of DEDSSDMT occurred with the steady expansion of feral animals (e.g. rabbits, cane toads) over the continent.

7 Solid-state fibrous veins?

Recent investigations into the nature of vein formation have focused on the length scale of the transport mechanism that provided the vein material (Fisher & Brantley 1992, Bons & Jessell 1997). Here we would like to investigate another aspect of vein formation, namely whether it is possible to develop vein-like structures without the need for a void to have been present. Bons & Jessell (1997) and Janssen & Bons (1996) provide examples of this type of behaviour (the former where a fibrous vein like material develops in a temperature gradient!). Figure 9 shows the development of a "elongate blocky" microstructure (Fisher & Brantley 1992) which has formed by the competitive growth of a set of nuclei into a single host. Since the boundaries between nuclei appear to be relatively stable, and the growth rates into the host grain relatively equal, a set of elongate sub-parallel grains develops, in an area in which there is no evidence of a migrating open boundary. Another interesting phenomenon is that of "winners" and "losers", i.e. grains that for some reason keep on growing at the growth front, whereas others lose contact with the front and stop growing further. In vein-growth, the winners are typically grains with certain favourable crystallographic orientations (Bons 1997); the reason for the purple grain's "victory" in Fig 9 remains unknown

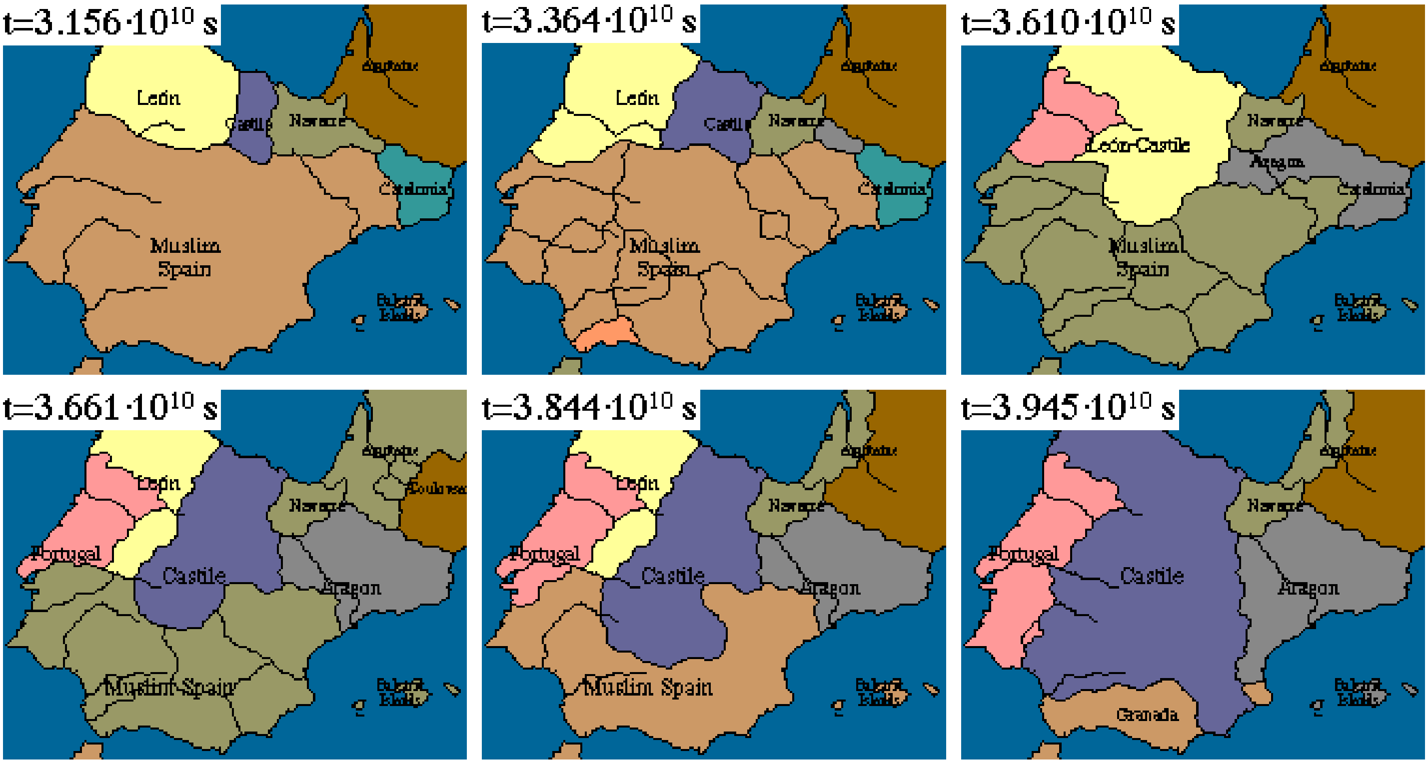


Figure 9. Between about 1000 and 1492, the small states on the northern edge of the Iberian Peninsula extended to the south, at the expense of the Muslim state in the south. A new player came into the game at 1094, when the county around Porto became independent and Alfonso I proclaimed himself king in 1139. Portugal, LeÛn, Catile and Aragon

then all extended at approximately the same rate to the south. Momentum was not lost on reaching the other side of the peninsula, as the subsequent extensions to Italy, the Americas and Asia prove.

8 Porphyroblast Rotation?

The correct interpretation of inclusion trail geometries in porphyroblast geometries became one of the more contentious issues in structural geology conferences in the 1980's (Bell 1985, Bell *et al.* 1992, Vernon 1988). In particular the spiral inclusion trails in garnets were re-interpreted as reflecting alternating compression-extension cycles, rather than reflecting the rotation of the porphyroblasts with respect to geographic reference frames. In the example shown here we provide what we believe is unequivocal evidence that in some cases rotation did in fact occur (Fig 10). This evidence has since been thrown in to doubt by a group of Spanish geologists who claim that the apparent rotation seen in France is actually due to the use of Madrid as a reference frame, and in fact it was Spain that rotated and the causative body in France was actually standing still. Clearly this topic is not dead yet, but is still a casus belli among geologists. It has been recognised by several workers that the key to solving this issue lies in the Pyrenees (Lister *et al.* 1986, Passchier & Speck 1994, Aerden 1995).

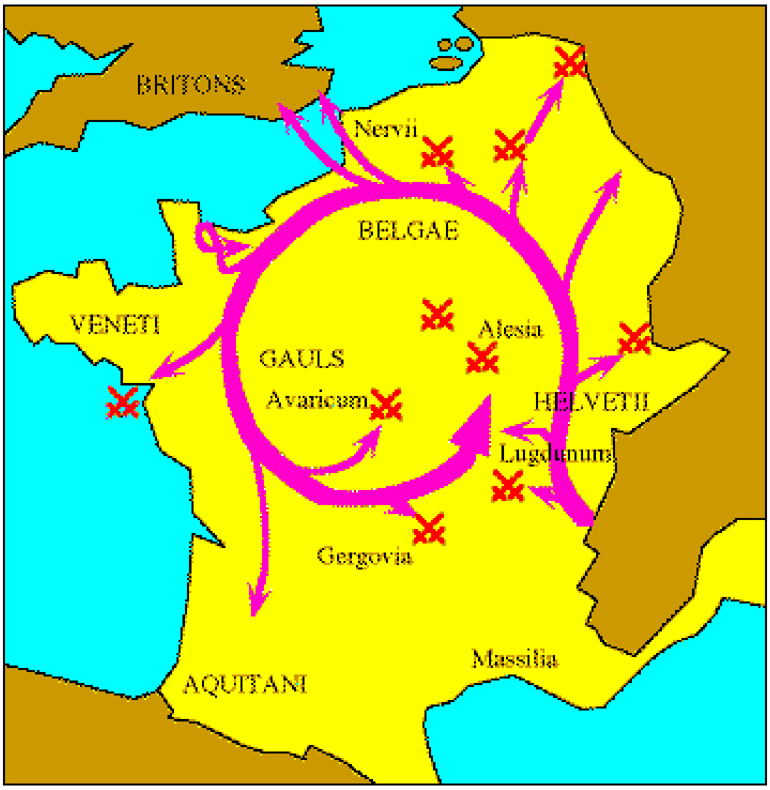


Figure 10. Between the years 58 and 51 BC, Julius Caesar conquered the whole of Gaul (the whole of Gaul? Not really, but that is another story.... see Goscinny & Uderzo, 1990). The map of this conquest (after Kinder & Hilgemann 1978) raises the question: did Caesar move around or did he stand still while Gaul rotated? Caesar himself was quite aware of the rotation issue and is known to have studied the rotational behaviour of rigid objects by throwing dice, while frequently exclaiming "alea iacta est!".

Warning!

The experiment described here has not finished yet and hopefully will not do so for a long time. We do invite all interested workers to share our study of the fascinating processes that are revealed. However, a strong warning should be made against any attempt to interfere with the experiment, as any attempt to control or change developments in the sample or even a tiny sub-region of it may lead to unexpected and probably violent reactions. Even those who have strong backing from government and/or industry should heed this warning!

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Great strides in Science and pushing back the frontiers of Knowledge can only be done with the intellectual, moral, physical, psychological and culinary guidance, challenge, sustenance and support by many friends, sponsors, family, pets, associations, clubs, government agencies, private institutions, teachers, students and even opponents in the past and present (and D.v. in the future) of which we would like to acknowledge at least a few, namely Monash University (and its generous Logan Fellowship Scheme), the Australian Research Council, the AGCRC, the American Geophysical Union, our history teachers at the Christelijk Lyceum Dr. W.A. Visser 't Hooft, The University of Utrecht, Imperial College, the Geologisch College Miàlnir, the Utrechtse Geologen Vereniging, the Royal Army (of the Netherlands of course), the Koninklijk Geologisch en Mijnbouwkundig Genootschap, the Royal Society for the Protection against Cruelty to Animals, the American Association for the Advancement of Science, the Geological Society of Australia, the Monash University Geological Society, The Department for Education, DEETYA (but in particular not the minister, Senator Vanstone), the Victorian Institute of Earth and Planetary Sciences.

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