PROPOSAL TITLE	Evolution of Rift and Rifted Margin Sedimentary Basins: Numerical Investigation of Tectonics, Sedimentation, and Salt-Related Structures of the Atlantic Canada Margin and Elsewhere	

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STAKEHOLDERS	Geodynamics Group, Dalhousie University IBM (Partner Funding Company) NSERC (Partner Funding Agency) CFI (Partner Funding Agency)

ENCLOSED DOCUMENTS	Summary Research Proposal Financial Proposal Stakeholder Statement of Support	

SUMMARY OF PROPOSED RESEARCH

Summary of ACPI Proposal

The research proposed here is related to the larger goals of the Dalhousie geodynamics numerical modelling laboratory (outlined below). It is a component in which existing and nearly completed finite element numerical modelling techniques will be applied to fundamental problems related to the evolution of sedimentary basins in two dimensions. Research will focus on: crustal deformation during rifting and rift reactivation; salt tectonics induced by thin-skinned tectonics and differential loading; and the behaviour of the sedimentary basin as a system in which these processes interact. The models will be process-based and will predict the dynamics (not kinematics) of the system. The research will focus on applications and not on software development.

Partial funding is requested from ACPI for two post-doctoral researchers to undertake four research projects.

1) A study of the tectonic control of sedimentary basins, particularly processes related to strain localization, the formation of fault and shear zones, and the reactivation of these zones, both in the basement and within the basin sediments.
2) The effect of regional tectonics within the sedimentary section on the mobilisation of salt and the development of finite amplitude salt structures.
3) The role of differential sedimentary loading in salt mobilisation, and the dependence of salt tectonics and the thermal evolution of the system on sediment properties.
4) The behaviour of sedimentary basins containing salt as a system in which the interactions among the processes studied in projects 1-3 are linked.

Applications will include case studies from the Atlantic Canada margin, generic problems, and case studies from other margins that provide particularly good examples of specific problems.

The proposed research is consistent with the ACPI Hydrocarbon Evaluation research theme. It falls within the ACPI special interest areas with regard to Basin Analysis and Architecture, in general, and the deepwater Scotian margin salt province and Jeanne D'Arc basin, in particular. Sedimentation versus tectonics (or better expressed as tectonic-sedimentation interactions) is a core component.

Associated Activities and Context for This Proposal to ACPI

The Dalhousie Geodynamics Group has proposed to IBM, NSERC and to the Atlantic Innovation Fund (PPSC-AIF) to establish and develop a numerical, computer based, modelling laboratory. The stated goals are fourfold: 1) to develop numerical techniques and tools (computer software) designed to improve significantly our understanding of the formation and evolution of sedimentary basins; 2) to demonstrate how this software can be applied to improve oil and gas exploration strategies in Atlantic Canada and globally; 3) to transfer this technology to the private sector and institutions focussed on petroleum exploration, and; 4) to seek to commercialize the software.

In doing so, we will achieve the following objectives: 1) establish a numerical modelling laboratory that develops software in support of petroleum exploration and that collaborates with, and provides services for industry and others in the use and application of these software tools; 2) develop a three-dimensional understanding of the factors that control the framework of the sedimentary basins of Atlantic Canada through numerical modelling and comparison of model results with data; 3) develop process-based models for sedimentary basins in the presence of mobile salt, and: 4) improve our understanding of the thermal history of the sediments in relation to burial, structural evolution and the influence of salt tectonics.

These proposals have been successful and will result in the establishment of a new IBM-SUR Computer Facility at Dalhousie, funding from AIF for the development of new three-dimensional finite element software, and from NSERC for matching funding for the AIF and the ACPI proposals. This means that the associated activities necessary to complement the research proposed here are either already started or will be in place during the Autumn of 2002. These funds provide the framework for the next five-year phase of our research. This proposal to ACPI is for funding for applications to geological problems. It complements but does not duplicate our other research.

RESEARCH PROPOSAL

Introduction and Background

The proposal is based on two lines of research, the tectonics of the crust and mantle lithosphere beneath sedimentary basins and the tectonics of salt within the sedimentary basin. We first propose to apply numerical models to each of these problems separately. Secondly, we will amalgamate both lines of research to improve understanding of the dynamics of sedimentary basins containing salt that are driven tectonically and by sediment loading. In this section a brief introduction is given for each line of research.

Tectonic Control of Sedimentary Basins

Sedimentary basins are depressions in the Earth's surface where sediments accumulate. They form as a consequence of deformation and subsidence of the Earth's outer strong rind, the lithosphere. Deformation may also cause uplift of the surface and many sedimentary basins undergo superimposed phases of subsidence and uplift. The primary mechanisms for the formation of sedimentary basins are lithospheric extension, which creates rift basins and passive continental margins, and lithospheric contraction, which creates forearc and foreland basins. Lithospheric extension and contraction that are normal to plate boundaries can be addressed to first order with plane-strain vertical cross-section models. However, if the motion includes a transcurrent component parallel to the plate boundary, leading to transtension or transpression, the problem needs to be addressed in 2.5 or 3 dimensions.

A crucial problem at the heart of rift and passive margin geometries concerns partitioning of strain and deformation during rifting. Even an investigation of the control of symmetry and asymmetry requires a solution of this problem and there is merit in both 2D and 3D approaches. Deformation is both focussed (on faults and within shear zones) and distributed (where there is no localization) and, in our opinion, the key to rift geometries is an understanding of the reason for this partitioning of distributed and focussed strain. Progress will be made by combining model and observational studies and we have already developed and tested some modelling techniques. Rifting processes are also one target of the NSF Margins program and our work is intended to complement the observational component of this initiative. Our proposed research is also intended to provide insight into the development of sedimentary basins that are superimposed on the lithospheric rifting fabric and that may be modified by reactivation of this fabric, as on the Grand Banks margin.

Two end-member hypotheses to be investigated are that either reactivation of existing faults/shears, or strain softening/hardening of newly developed ones are the primary controls on rifting fabric. Our initial approach to these problems has been to solve Stokes flow problems at the scale of the lithosphere and sublithospheric mantle. The 2D cross section coupled thermal-mechanical ALE FE models (e.g. Huismans and Beaumont, 2002 and submitted; Pysklywec et al., 2000; Pysklywec et al., in press) have 200x100 (or higher resolution) Eulerian meshes, 700 x 300 Lagrangian meshes, a domain of approx. 2000x600km, and are driven by specified velocity boundary conditions and internal density variations. The surface is a deformable stress-free boundary which provides an accurate calculation of the gravitational forcing by topography. Rheologies include cohesive (von Mises), and pressure sensitive (Drucker-Prager) frictional plasticity, thermally activated creep (grain-size sensitive, power-law, and Peierl's law) and may include strain rate- or strain-softening/hardening. Inclusion of strain-dependent material behaviour allows us to investigate strain partitioning during deformation in addition to that predicted by the basic rheologies. Our provisional conclusion like that of others, is that strain softening is required for plate tectonics to operate. Plate boundaries with Byerlee's law and laboratory based creep rheologies are too strong and do not localize deformation. Softening/hardening is also necessary for reactivation to be important, without them there would be no weak faults/shears to reactivate. Examples of the model results (Huismans and Beaumont, 2002, see Appendix 1) demonstrate the sensitivity of rift geometries to initial conditions, rifting velocity, and strain softening in the frictional regime. They show symmetric (McKenzie type) and asymmetric (Wernicke type) styles can be produced when strain softening is included.

The next steps are of three types: 1) to broaden the range of model experiments to determine the sensitivity to other material (see also Frederiksen and Braun, 2001) and thermal initial conditions, and to other processes e.g. decompression melting and sedimentation during rifting; 2) to investigate the post-rift evolution and the sensitivity of the evolving passive margin to extensional and contractional reactivation as it cools, and; 3) to parameterize possible natural fault and shear zone softening and hardening mechanisms (e.g. observational research on 'weak faults', e.g. Rutter et. al., in press; laboratory observations, e.g. Bos and Spiers, 2002; the 'damage' approach to fault zone weakening e.g. Tackley, 2000), and to determine the model sensitivity to these mechanisms. This approach will be undertaken together with the development of improved numerical techniques, first in 2D (for example using high resolution meshes in parallel codes, and adaptive mesh refinement to follow local shear intensification), and later in 3D as the development of the AIF funded research proceeds.

The lack of strong self-organized patterns in rifts also suggests that other effects compete with the mechanism proposed above. By introducing initial weak structures into the FE models it will be possible to determine the threshold level of weakening and density of these structures required to interfere with self-organization. This approach offers a possible way to address the relative roles of reactivation of pre-existing fabric versus the creation of new rifting fabric.

Salt Tectonics

The second line of research concerns the role of 'salt' layers deposited as part of the sedimentary fill of sedimentary basins. Salt is much weaker and less dense than most other sediments and commonly becomes mobile, deforming under the weight of sediments that accumulate above the salt and in response to tectonic stresses. Salt tectonics has a long and rich history, particularly as salt mobility is economically important because it influence several aspects of the petroleum system, (e.g. Jackson et al., 1995; Alsop et al.,1996; Vendeville et al.,2000; and Cobbold 1993).

In the last decade the petroleum industry has become increasingly interested in the oil and gas potential of reservoirs in deep water slope and rise regions of passive continental margins (e.g. Mohriak and Talwani, 2000). Many of these regions are also salt provinces, e.g. parts of the West African margin, the Gulf of Mexico, and the Santos Basin, Brazil. Parts of the Atlantic Canada margin are also salt provinces as is the Paleozoic Maritimes Basin.

The passive margin salt tectonics problem has been addressed through direct, mainly seismic, observations to determine the current geometries of salt related structures, balanced cross section palinspastic restorations which provide information on the system evolution, mathematical analysis of simplified models of systems with properties like those of salt (largely focussed on boudinage, folding and diapiric instabilities), laboratory analogue models, and numerical models. Among the models, scaled analogue experiments have probably been the most successful in providing insight into salt tectonics. In particular, such models have taken salt tectonics well beyond considerations of diapiric piercement of overburden initiated by small gravitational instabilities. However, questions have also been raised concerning their scalability to natural systems (Leroy and Triantafyllidis, 2000).

Two research themes which we propose to pursue concern salt mobilisation under differential loading, particularly associated with progradation of sediment wedges (e.g. Vendeville et al., 1992 experiment 146; Koyi, 1996), and the effect of externally applied, and internally generated, extensional and compressional tectonics on salt tectonics and the feedback into the larger scale deformation. Jackson and Vendeville (1994), for example, convincingly argue that regional tectonic extension of overburden is a key factor that causes reactive salt diapirism and may lead to active piercement if the overburden is thinned beyond a critical thickness.

The wholesale detachment and downslope gravitational gliding/sliding of passive margin sedimentary wedges represents a composite system. Extension of the upper part of the wedge may trigger diapirism. The contractional tectonics of the wedge toe produces a fold-thrust belt which may contain characteristic salt structures such as salt tongues, sheets, stocks and walls as integral parts of a nappe system (Vendeville, sub.). Lehner (2000) analyses the underlying squeeze flow and provides a simplified theory for the failure of the overburden. We are using these predictions for a starting comparison with the numerical models.

Jackson (1995) provides an interesting perspective in which he divides the history of salt tectonics into the pioneering era, the fluid era, and the brittle era. The research proposed here is focussed on the ‘brittle’ treatment of salt overburden but also allows for ductile rheologies. Jackson remarks in his postscript that, ‘In theory, a supercomputer groaning under the weight of appropriate algorithms and incorporating a realistically large number of variables could simulate a full range of salt tectonics by forward modelling’. He then points out that we lack the necessary knowledge of the data (model properties) and that such an approach could never verify the hypotheses built into the algorithms. Exactly the same problems confront numerical models of lithospheric deformation that have been used to gain insight into orogenesis and rifting, yet considerable progress has been achieved. The motivation and approach in these numerical models differs from Jackson’s groaning supercomputer because the models are designed as a set of numerical experiments which start from simple problems, often for which solutions already exist, then progress through successively more complex rheologies and boundary conditions. In this way a template of model solutions and behaviours is constructed to characterize the influence of the various material properties, rheologies and boundary conditions. At best the models represent simplifications of the natural system. However, even the knowledge of the way the model systems operate leads to important insight and the development of hypotheses concerning the operation of the natural system. Such insight is vital, particularly when the system instabilities, dynamics and feedback loops are not intuitively understood.

The rationale for the numerical experiments is exactly the same as that for the laboratory analogue models. They are complementary and have respective advantages and disadvantages. There is no intent here to claim superiority for the numerical approach. In fact, it is only recently (e.g. Schultz-Ela and Jackson, 1996; Kaus and Podladchikov, 2000; and Podladchikov et al., 1993) that numerical models of salt tectonics have become comparable to the analogue ones. However, it is fair to point out that among the potential advantages of accurate numerical calculations is the ability to define materials with desired properties without the restrictions of scalability required in the laboratory experiments. This is a particular advantage for the thermal-mechanical model experiments because it is difficult to find materials that scale correctly for both thermal and mechanical properties. In addition, information on the model results in regard to deformation, strain, strain rate, temperature, evolving material properties etc. are all normal outputs from the model experiment and there is no need to devise techniques to probe the experiment for this information. Other less complex but equally important things including sediment compaction, surface processes and isostasy are also more easily achieved in numerical experiments. However, it remains to be demonstrated that the numerical experiments are sufficiently accurate.

The minimum requirements for numerical experiments concerning salt tectonics is an ability to calculate accurately deformation of sediments and salt driven by gravitational (buoyancy) and boundary forces using appropriate frictional-plastic and thermally-activated ductile rheologies. The next stage is to compare these results with models with elasto-plastic rheologies. Given that salt commonly remains mobile during continued accumulation of overburden, downbuilding or passive piercement, in addition to upbuilding or active piercement, the numerical experiments should also include an upper free surface (subject to hydrostatic pressure if the section is submarine) which both deforms and is modified by sedimentation and erosion. This is a critical component because salt tectonics reflects the interplay between tectonic and gravitational forces. Both types of force are very sensitive to the position of density interfaces, particularly the surface. In addition, the role of evolving fluid pressure within the sediments is certainly important under some circumstances, as is thermal buoyancy, and the isostatic compensation of the system.

Our current numerical capabilities (see Methodology section) satisfy all of the above requirements for plastic-viscous models in 2D, except for dynamical calculations of fluid pressure. Although our previous research has not focussed on salt tectonics, the ALE finite element methods have proven to be successful in analogous problems concerning deformation and flows at the crustal scale which involve weak materials flowing through channels under gravity forcing and interacting with surface denudation and sediment deposition (Beaumont et al., 2001a; Beaumont et al., 2001b. We have also developed and used surface process models (e.g. Kooi and Beaumont, 1994, Johnson and Beaumont, 1995) and have coupled them to crustal scale tectonic models (e.g. Beaumont et al., 1992). We will use similar surface process models in parts 3 and 4 of this research project.

Scope

The scope of the project is defined by the objectives listed below. It is a study which will employ numerical model experiments concerning crustal/lithospheric and salt tectonics, primarily in 2D cross section. It is designed to demonstrate the capabilities of the numerical modelling techniques, to apply these techniques to case studies and generic problems, and to improve the understanding of sedimentary basins as a dynamical system. The case studies will include examples from the Atlantic-Canada margin.

Objectives

The particular focus of the projects proposed here is fourfold. 1) The role of crustal deformation during rifting and tectonic reactivation in determining the evolving geometry and fault distribution in overlying sedimentary basins and converse effects of sediments on the crustal deformation. 2) The mechanisms of salt tectonics caused by, thin-skinned tectonics and, 3) differential loading. 4) The dynamics of sedimentary basins in which all of these factors operate and interact.

The fundamental problems to be addressed are outlined below. At this point we note that software development is a minor component of this research. When software development is necessary it will be funded from matching funds, not ACPI funds.

1) Deformation of the crust and mantle lithosphere during rifting and reactivation of rifts and rifted margins.

   This project is a continuation and refinement of the research on lithospheric extension and the role of strain-dependent material properties in creating localized shears and fault zones (Appendix 1). The focus will be at a smaller scale and in a sedimentary basin setting in which the dynamical interactions between faulting and sedimentation become important. In some initial model experiments Susanne Buiter (visiting postdoctoral fellow from Bern) has shown that the styles of crustal faulting in the model experiments can be very different depending on whether there is, or is not, syntectonic sedimentation in the extensional grabens. This result is not surprising given what we have learned about coupling between surface processes and tectonics in thrust belts and orogens, and a similar feedback between sedimentation and tectonics has been demonstrated by Ritske Huismans for the lithospheric scale models. However, it is potentially a very important result that suggests the structural style of a rifted margin may depend on sediment supply during rifting. The sediments may control the geometry of the sedimentary basin and the distribution of faults in the crust.

2) Salt tectonics by active, passive and reactive piercement induced during regional thin-skinned (i.e. within the sedimentary section) tectonic contraction and extension.

   This is a new area of research for the Dalhousie Geodynamics group. We would like to thank Hemin Koyi (U. Uppsala), Yuri Podladchikov (E.T.H.), Chris Talbot (U. Uppsala) and Bruno Vendeville (U.Texas at Austin) for helpful advice and for providing copies of reprints and preprints concerning salt tectonics. The proposed methodology is described below and examples of preliminary model experiments are given in Appendix 2. The aims are to demonstrate the use of numerical experiments in salt tectonics, a field that is developing but is not mature, and then to develop this research in a systematic manner through generic and case studies. The initial focus will be on thin-skinned tectonics as a trigger for diapirism under frictional-plastic and mixed viscous/frictional-plastic overburdens. The purpose is to translate the analogue model research in this area done at the Applied Geodynamics Laboratory, University of Texas at Austin and elsewhere, to the numerical model equivalents to test their scalability, and then to investigate the numerical model behaviour under a range of controls. What determines characteristic length and timescales? How do the extensional and contractional systems differ? There is a significant literature on stability analysis but less is published on finite deformation.

3) Salt tectonics induced by differential loading.

   The objective in problem 3 is to improve the understanding of the mobilisation of salt in the form of squeeze flows by differential loading. This research parallels project 2 and will use similar techniques. It is, however, distinct because the driving force for salt tectonics is the differential loading from overburden, for example an overlying prograding sedimentary wedge. The models require the introduction of surface processes, most importantly sedimentation in order to develop a prograding wedge. The wedge must also be incorporated as an integral mechanical component of the model and its deformation calculated.

Ultimately problems 2 and 3 converge and overlap. This is particularly true when considering the wholesale gliding of passive continental margin sedimentary prisms that have detached on salt as a consequence of differential loading. In such cases the thin-skinned tectonics above the squeeze flow is driven by the differential loading.

4) The sedimentary basin as a system: linked basement and salt tectonics.

The objective here is to address the tectonics and sedimentation of sedimentary basins as a system. What are the dynamical properties of this system? How do the interactions and feedback loops operate? What can be learned about the basement tectonics from the deformation style of the sediments, including the salt. Conversely, how does basement reactivation, for example, influence sediment deformation in the presence of salt and syntectonic sedimentation?

Research Team

Dalhousie Geodynamics Group
Christopher Beaumont, Canada Research Chair in Geodynamics
2 Postdoctoral Fellows to be appointed. Positions will be advertised, and may also be offered to current postdoctoral fellows who are highly qualified.
Supported by:
Philippe Fullsack, mathematician, numerical analyst and creator of the finite element codes listed below;
Sergei Medvedev, postdoctoral fellow, mathematical geophysics;
Ritske Huismans, postdoctoral fellow, structural geology, numerical modelling, rifted margins;
Lykke Gemmer, postdoctoral fellow, geology, basin analysis, numerical modelling, salt tectonics;
Bonny Lee, research technician, computer systems;
Mai Nguyen, research technician;
Steven Ings, summer student, M.Sc. student from September 2002.

Facilities

The facilities are those of the Dalhousie Geodynamics Group within the Oceanography Department. They include the necessary office and work space, workstations, plotters, scanner and access to the 48 processor Dalhousie IBM Power 3 SP parallel computer. Pending improvements to these computing facilities are discussed in the budget section.

Methodology

We propose to use finite element techniques developed by the Dalhousie Geodynamics group to formulate and undertake the numerical experiments. We also propose to compare and contrast these results with observations in case studies and with analytical studies of instabilities in elastic/plastic and viscous/plastic laminates, scaled physical laboratory models, and other numerical results.

The field of numerical modelling of lithospheric deformation and associated geological process, including development of thin-skinned fold-and-thrust belts and sedimentary basins, has made significant advances in the last five years. Approaches using large deformation finite element techniques and other methods have already demonstrated that numerical modelling experiments can make significant contributions to the understanding of tectonics and sedimentation as a dynamical system. The proposed research is designed to exploit these modelling techniques by applying them to rifted margins and to sedimentary basin systems containing salt.

Information on the capabilities of our finite element modelling techniques in regard to lithospheric extension and salt tectonics is provided in the Appendices to this proposal. Funding for further development of these techniques has been secured from NSERC, AIF and IBM. An outline of the current techniques is included below in order to describe the methodology properly. We understand (John Hogg, pers. comm.) that ACPI does not wish to fund software development and we therefore agree that any limited development will be funded from matching, not ACPI funds. The development of the 3D finite element code is a separate project and no funds are requested from ACPI for this purpose.

The currently available thermal-mechanical computational techniques are listed below. The following is a simplified explanation of the terminology. '2D' means two-dimensional, either horizontal or vertical plane. 'Serial' means that that a single computer processor is used to make the calculations. 'Parallel' means that the code has been designed to make the calculations simultaneously using multiple processors on a parallel computer (e.g. the Dalhousie IBM SP) or a cluster of computers. 'Structured' means that the finite element grids/meshes have a topology in which there is a fixed number of nodes/elements in each coordinate direction, though the size of the elements may vary spatially and with time. 'Unstructured' means that the grids/ meshes do not have the uniform topology of the structured ones, thereby allowing mesh density to vary so that the model resolution can be greater where necessary. 'Adaptive' means that the grids/meshes may change during a model calculation according to one or more criteria designed to optimize the calculation, e.g. increase resolution in shear zones. ALE means Arbitrary-Lagrangian-Eulerian, a technique in which the finite element calculation is Eulerian but is coupled to a Lagrangian advection process. The Eulerian grids/meshes may be modified/updated during the calculation but such modifications are arbitrary in that they are not designed to follow the material trajectories as would be the case in an updated Lagrangian approach. Instead, a second grid, which is Lagrangian is used to advect the material property fields and these are interpolated onto the adapted Eulerian grids/meshes each timestep before the finite element calculation. This approach allows calculations to be made for large displacements / deformation / strains without the associated unacceptable distortion of a Lagrangian finite element mesh. The method also has the advantage that material fluxes through moving boundaries can be included, thereby allowing deposition, denudation and adaptation of true free surfaces to be calculated. This is particularly important for the types of problems considered here.

MICROFEM and SOPALE (both 2D coupled thermal-mechanical serial structured ALE FE codes that use 4-noded quadrilateral elements).
The Huismans and Beaumont model results (Appendix 1) and the salt models (Appendix 2) used SOPALE (mesh sizes are approximately 151x401 and 81x801).

MOZART-P/S/Q4/ALE (2D parallel structured ALE finite element code that uses 4-noded quadrilateral elements).
This code has been developed and tested against some benchmark problems. It is the parallel equivalent of SOPALE and will provide higher resolution (potentially meshes up to 600x800 in 2D on 16 processors of the Dalhousie SP).

MOZART-S/U/T6/L (2D serial unstructured adaptive Lagrangian finite element code based on 6-noded triangular elements).
The advantage of this unstructured code is that the grids can be adapted to give increased/decreased resolution where necessary, thereby allowing more accurate calculations where model property gradients are highest, e.g. shear and fault zones.

These codes, together with the parallel version of the unstructured adaptive one, will provide the basic tools for the proposed research.

The finite element calculations are velocity-based and are designed for large deformation fluid Stokes flows (Fullsack, 1995). A range of rheologies is possible including incompressible plasticity (Von Mises, frictional Coulomb/Drucker-Prager), thermally activated power-law creep, grain-size dependent diffusional creep, Peierl's law creep, in addition to linear Newtonian viscous flow. Plastic calculations are based on Levy-Mises theory (Malvern, 1968, Willett, 1999). Simple parameterizations of strain dependent frictional-plastic and ductile rheologies have also been used extensively (see Appendix 1). No difficulty is anticipated in adding appropriate salt rheologies based on laboratory experiments, 'damp', dry, and grainsize/thermal dependencies. However, initial calculations will consider 'salt' to be Newtonian with a large range of possible viscosities. This approach is valid because salt is very weak by comparison with most overburdens and therefore its detailed rheology is less important than that of the overburden.

Activities and Milestones

YEAR ONE
Projects 1 and Projects 2/3 will be undertaken in parallel.
Initial model experiments will use the existing SOPALE computer code modified to include sediment compaction, isostasy and appropriate surface processes for the salt tectonics experiments.
Suitable natural examples of type problems will be chosen for case studies and access to proprietary data and advice will be sought when necessary.
Case studies will include examples from Atlantic Canada.
Initial low resolution model results will be compared and contrasted with theory, natural examples, analogue models, and other numerical models and the results will be presented at scientific meetings and to industry.

YEAR TWO
Low and high resolution model experiments will be undertaken and the results compared to assess accuracy. Comparisons will also be made with results obtained using the unstructured code, MOZART-S/U/T6/L.
Project 4 will be initiated.
Manuscripts will be prepared for publication.

Results will be presented at scientific meetings, to industry, and made available from the group website.
This is the time when we will seek the maximum interactions with knowledgeable researchers in academia, government and industry.

YEAR THREE
Complete 2D model experiments.
Prepare and publish papers, place results and animations on website, showcase and disseminate results.
Undertake low resolution 3D numerical models if computer code is complete.
Prepare and offer short course on the research and the modelling techniques.
Exploit any opportunities that have arisen during the project.
Develop proposals for the next phase of research in consultation with industry.

Brief Progress Report

In the time since this proposal was first submitted (Feb 2002) there has been significant progress on this project and related research.

1) The PPSC-AIF and NSERC Research proposals have been funded.
2) Huismans and Beaumont paper is published, Geology, v.30, p211-214, 2002. Huismans and Beaumont manuscript has been submitted to J.G.R., June 2002.
3) Research on salt tectonics started Spring 2002. Dr. Lykke Gemmer and Steven Ings are working on 2D numerical models of boudinage of overburden above salt and on salt squeeze flows beneath prograding overburden.
4) Dr. Bruno Vendeville requested, and we have agreed, to give an invited presentation at the GSA Annual Meeting in Denver, October 2002, on Viscous Creep of Substratum and its Tectonic Effect on Viscous and Brittle Overburden: Applications of Salt Basins and Continental Plateaus.
5) Dr. Lykke Gemmer, who is a postdoctoral fellow from Denmark working with our group, has expressed interest in the salt tectonics position to be funded if this proposal is successful. In my judgement she is highly suitable and is already working on the salt tectonics problem. Her CV is available at http://adder.ocean.dal.ca/lykke/index.html.
6) Our 3D finite element code development team (Fullsack, Huismans and Gemmer) is currently at the Australian National University developing the Phase 1 3D code with Dr. Jean Braun. This work is funded by PPSC-AIF.
7) Discussions with IBM concerning selection of computer hardware for the IBM SUR Computational Facility are underway.
8) Lykke Gemmer and Steven Ings will attend Mark Rowan's short course on salt in Halifax this Autumn.
9) Animations of example model results are available:
    - Asymmetric Lithospheric Extension
      http://adder.ocean.dal.ca/anim/C23HMa.gif
      http://adder.ocean.dal.ca/anim/C23HM_str.gif
    - Thin-Skinned Fold and Thrust Belts
      http://adder.ocean.dal.ca/anim/RBRTP-17d_fast.gif
    - Gravitational Instability of Frictional Overburden above Viscous ('Salt') Substratum
      http://adder.ocean.dal.ca/anim/salt1.gif

Deliverables

The deliverables are as follows:

1) The results of the research projects and the knowledge gained from the research proposed here which will be appropriately disseminated;
2) The methodology and techniques used in the computer software (funded by PPSC-AIF);
3) The computer software per se, which we will seek to commercialize as a component of the PPSC-AIF project;
4) The highly qualified personnel who have received training during the project and will be available for employment.
5) The tangible products, published papers, website information, and short course material.

Relevance and Significance

The proposed research is highly relevant and we anticipate significant results. We seek overall progress in the scientific understanding of the dynamics of sedimentary basins and the control of sedimentary basins by crustal tectonics. This improved understanding will be of practical value to the petroleum industry by improving exploration strategies, particularly in sedimentary basins involving salt tectonics. The results should be of local and global significance because the research broadly based and will include a range of case studies.

Relationship to the ACPI Proposal Criteria

The proposed research is consistent with the Hydrocarbon Evaluation research theme. As shown in the budget, the secured leveraged funds substantially exceed the request from ACPI. The proposed research is led by the Dalhousie University Geodynamics Group. It is linked to the broader aspects of Oil and Gas R&D in Atlantic Canada through the PanAtlantic Petroleum Systems Consortium (PPSC). In addition, there are links to IBM Watson Laboratories, New York (through the SUR grant), links through collaboration on thin-skinned fold-and-thrust belts with Dr Glen Stockmal, GSC Calgary, links to research on the mechanisms of graben formation with Drs Susanne Buiter and Adrian Pfiffner, Univ. Bern, Switzerland, and links with Dr. Jean Braun, Australian National University, in regard to 3D finite element software development. The results have the potential to be applicable to a wide range of problems concerning sedimentary basins and hydrocarbon activities in general, and specifically to the crustal and salt tectonics of the Atlantic Canada margin and Maritimes Basin. On the basis of the example results provided in the Appendices, we believe the research is technically sound, and feasible. It addresses issues of relevance to Atlantic Canada, and is relevant to other salt provinces in Canada and globally. The research is innovative in that, to the degree that it is unique, it offers significant advances in the application of numerical techniques to actual geological problems concerning sedimentary basins.

References

Alsop, G.I., Blundell, D.J., and Davison, I., eds., 1996. Salt Tectonics, Geological Society Special Publication 100, 310 pp.

Beaumont, C., Fullsack, P., and Hamilton, J., 1992. Erosional control of active compressional orogens, in: K.R. McClay ed., Thrust Tectonics, p. 1-18. Chapman and Hall.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., and Lee, B., 2001a. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focussed surface denudation, Nature, v.414, p.738-742.

Bos, B., and Spiers, C.J., 2002. Frictional-viscous flow of phyllosilicate-bearing fault rock: Microphysical model and implications for crustal strength profiles, Journal of Geophysical Research, v.107, 10129.

Beaumont, C., Jamieson, R.A., Nguyen, M.H, and Lee, B., 2001b. Mid-crustal channel flow in large hot orogens: results from coupled thermal-mechanical models, Lithoprobe SNORCLE Transect Report, v.79, p.112-170.

Cobbold, P.R., ed., 1993. New insights into salt tectonics, Tectonophysics, v.228, p.141-150.

Frederiksen, S., and Braun, J., 2001. Numerical modelling of strain localization during extension of the continental lithosphere, Earth and Planetary Science Letters, v. 188, p. 241-251.

Fullsack, P.,1995. An arbitrary Lagrangian-Eulerian formulation for creeping flows and its applications in tectonic models. Geophys. Jour. International, v.120, p.1-23.

Huismans, R., and Beaumont, sub. Symmetric and asymmetric lithospheric extension: Relative effects of frictional-plastic and viscous strain softening, submitted to Journal of Geophysical Research, June 2002.

Huismans, R., and Beaumont, C., 2002. Asymmetric lithospheric extension: the role of frictional-plastic strain softening inferred from numerical experiments, Geology, v.30, p.211-214.

Jackson, M.P.A., 1995. Retrospective salt tectonics, in: Jackson, M.P.A., et al., Salt Tectonics: a Global Perspective, Am. Assoc. Petroleum Geologists, Memoir 65, p.1-28.

Jackson, M.P.A., and Vendeville, B.C., 1994. Regional extension as a geologic trigger for diapirism, Geol. Soc. Am. Bull., v.106, p.57-73.

Jackson, M.P.A., Roberts, D.G., and Snelson, S., eds., 1995. Salt Tectonics a Global Perspective, American Association of Petroleum Geologists Memoir 65, 454 pp.

Johnson D.D., and Beaumont, C., 1995. Preliminary results from a planform kinematic model of orogen evolution, surface processes, and the development of clastic foreland basin stratigraphy, in: S. Dorobek and G. Ross eds., Stratigraphic Evolution of Foreland Basins, SEPM Special Publication v.52, p.3-24.

Kaus, B.J.P., and Podladchikov, Y.Y., 2001. Forward and reverse modeling of the three-dimensional viscous Rayleigh-Taylor instability, Geophys. Res. Letters, v.28, p.11095-11098.

Kooi, H., and Beaumont, C., 1994. Escarpment evolution on high-elevation rifted margins: insights derived from a surface processes model that combines diffusion, advection and reaction. Journal of Geophysical Research, v.99, p.12191-12209.

Koyi, H., 1996. Salt flow by aggrading and prograding overburdens, in: Alsop, G.I., et al. eds., Salt Tectonics, Geological Society Special Publication 100, p.243-258.

Lehner, F.K., 2000. Approximate theory of substratum creep and associated overburden deformation in salt basins and deltas, in: F.K. Lehner and J.L. Urai, eds., Aspects of Tectonic Faulting, Springer-Verlag, p.21-47.

Leroy, Y.M., and Triantafyllidis, N., 2000. Stability analysis of incipient folding and faulting of an elasto-plastic layer on a viscous substratum, in: F.K. Lehner and J.L. Urai, eds., Aspects of Tectonic Faulting, Springer-Verlag, p.109-139.

Malvern, L.E., 1969. Introduction to the Mechanics of a Continuous Medium, Prentice-Hall, New Jersey.

Marton, L.G., Tari, G.C., and Lehmann, C.T., 2000. Evolution of the Angolan passive margin, west Africa, with emphasis on the post-salt structural styles, in: W. Mohriak and M. Talwani eds., Atlantic Rifts and Continental Margins, Geophysical Monograph 115, American Geophysical Union, p.129- 149.

Mohriak, W., and Talwani, M., eds., 2000. Atlantic Rifts and Continental Margins, Geophysical Monograph 115, American Geophysical Union. 354 pp.

Podladchikov, Yu., Talbot, C., and Poliakov, A., 1993. Numerical models of complex diapirs, Tectonophysics v.228, p.189-198.

Pysklywec, R.N., Beaumont, C., and Fullsack, P., 2000. Modeling the behavior of the continental mantle lithosphere during plate convergence, Geology, v. 28, p. 655-658.

Pysklywec, R.N., Beaumont, C., and Fullsack, P., in press. Lithospheric deformation during the early stages of continental collision: numerical experiments and comparison with South Island, New Zealand, Journal of Geophysical Research.

Rutter, E.H., Holdsworth, R.E., and Knipe, R.J., in press. The nature and tectonic significance of fault zone weakening: an introduction, in: R.E. Holdsworth et al. eds., The Nature and Significance of Fault Zone Weakening, Geological Society Spec. Publ. 186.

Schultz-Ela, D.D., and Jackson, M.P.A., 1996. Relation of subsalt structures to suprasalt structures during extension, American Assoc. Petroleum Geologists Bull., v.80, p.1896-1924.

Tackley, P.J., 2000. The quest for self-consistent generation of plate tectonics in mantle convection models, in: M.A. Richards et al. eds., Geophysical Monograph 121, American Geophysical Union, p. 47-72.

Talbot, C.J., 1992. Centrifuged models of Gulf of Mexico profiles, Marine and Petroleum Geology, v.9, p.412-432.

Vendeville, B.C., sub. Salt tectonics driven by sediment progradation. Part 1. mechanics and kinematics (m.s. pers. comm.)

Vendeville, B.C., and Jackson, M.P.A., 1992. The rise of diapirs during thin-skinned extension, Marine and Petroleum Geology, v.9, p.331-353.

Vendeville, B.C., Jackson, M.P.A., and Schultz-Ela, D.D., 1992. Applied Geodynamics Laboratory, second semi-annual progress report to industrial associates for 1991, Bureau of Economic Geology, University of Texas at Austin, 49pp.

Vendeville, B.C., Mart, Y., and Vigneresse, J-L., eds., 2000. Salt, Shale and Igneous Diapirs in and around Europe. Geological Society Special Publication 174, 207 pp.

Willett, S.D., 1999, Rheological dependence of extension in wedge models of convergent orogens, Tectonophysics, v.305, p.419-435.

APPENDIX 1: ASYMMETRIC LITHOSPHERIC EXTENSION: THE ROLE OF FRICTIONAL PLASTIC STRAIN SOFTENING INFERRED FROM NUMERICAL EXPERIMENTS

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Abstract

Plane-strain thermomechanical finite element model experiments of lithospheric extension are used to investigate the effects of strain softening in the frictional plastic regime on the asymmetry of extension. Strain softening is considered in cases where the crust is either strongly or weakly coupled to the mantle, and as the extension velocity varies from 0.3 to 30 cm/yr. In the absence of strain softening, extension is symmetric (SS mode). When strain softening takes the form of a reduction in the internal angle of friction with increasing strain, lithospheric extension may be asymmetric at a lithospheric scale (AA mode), or exhibit crustal asymmetry concomitant with mantle symmetry (AS mode). The different styles depend on the relative control of the system by the frictional plastic and ductile layers, which promote asymmetry and symmetry, respectively. High extension velocities and weak ductile crust-mantle coupling tend to suppress the fundamental asymmetry induced by frictional strain softening. This is because they, respectively, increase the effective strength of the lower lithosphere and decrease the control by frictional plasticity.

Keywords: Lithosphere, extension, rifting, strain softening, numerical modeling.

Complete manuscript available from
http://is.dal.ca/~huismans/HuismansandBeaumont_Geology.pdf.

Conclusions

The factors controlling extension and the corresponding modes are summarized in Figure 5. All models described here have a two-phase development; phase one controlled by the frictional behavior and phase two controlled by the ductile rheology. The asymmetric AA mode is favored by strain softening of a coupled, cold frictional upper lithosphere, at low rifting velocities, whereas the AS mode occurs in the equivalent decoupled model. The symmetric SS mode is favoured by the absence of strain softening or by high rifting velocities. Asymmetry of conjugate passive margins at the crustal scale has been interpreted to indicate the AA mode (Wernicke and Burchfiel, 1982; Lister et al., 1986; Mutter et al., 1989; Boillot et al., 1992; Sibuet, 1992; Louden and Chian, 1999). The occurrence of the AS mode in the dynamical models is an alternative (Lister et al., 1991).

The SS and AA modes are respectively similar to the pure-shear (McKenzie, 1978) and simple-shear (Wernicke, 1985) kinematic models of lithospheric extension. In dynamical models frictional plastic strain softening can control which of these two styles is selected. This same mechanism may operate in natural systems. Our work differs from the Buck (1993) and Lavier et al. (1999) models in that the amount of strain softening is greater than that owing to loss of cohesion. Fault zones may also be weakened by static or transient high fluid pressures and mineral transformations (Sibson, 1990; Streit, 1997), and by the preponderance of phyllosilicates in deformed polymineralic zones (Bos and Spiers, in press). The results shown here are, however, model dependent and depend on the model mesh resolution. They demonstrate the feasibility of the mechanism, but more accurate, higher resolution model experiments are needed.

Figures:

Figure 1. A: Model geometry including weak seed (von Mises yield strength, σ_y), and velocity boundary conditions (*Vext, Vb*) with *Vb* chosen to achieve mass balance. Initial, laterally uniform temperature (*T*) increases from surface (0 ºC) in accord with uniform crustal heat production (0.8 $\mu W/m^3$) and basal heat flux (20 mW/m^2). Mantle lithosphere geothermal gradient is uniform and sublithospheric mantle is isothermal at 1330 ºC. Thermal conductivity is 2.25 W/m/ºC and thermal diffusivity is 1 x 10^{-6} m^2/s. Densities (ρ_0) are shown at 0 ºC and thermal expansivity is 3.1 x 10^{-5}/ºC. At right internal friction angle (Φ): initial Φ = 7º (solid lines) and strain (ε) softened, Φ = 1º (dashed lines) representative strength envelopes of coupled and decoupled models when *Vext* = 0.3 cm/yr. Frictional plastic strain softening with ε is shown at top. Effective viscosity $\eta_{eff} = A^{-1/n}\, e^{(1-n)/n}\, exp[\, (Q+pV)/nRT]$, where for wet quartz (Gleason and Tullis, 1995), initial constant A = 1.1 x 10^{-28} Pa^{-n}, power law exponent n = 4.0, activation energy Q = 223 kJ/mole, activation volume V = 0, and for dry olivine (Karato and Wu, 1993), A = 2.4 x 10^{-16} Pa^{-n}, n = 3.5, Q = 540 kJ/mole, V = 25 x 10^{-6} m^3/mole, e is second strain rate invariant, p is pressure, and R is gas constant. x and z are horizontal and vertical coordinates, t is time, Δx is total amount of extension.

B, C: Reference coupled model 1 [η_{eff}(wet quartz x 100)], no strain softening, showing deformed Lagrangian mesh, velocity vectors, and sample isotherms after extension of 120 and 211 km, respectively, for dashed area in A. Model layers denote upper and lower crust, strong frictional upper mantle lithosphere, ductile lower lithosphere, and ductile sublithospheric mantle. Scaling of quartz viscosity makes upper three layers frictional plastic. Note symmetric extension. Color versions at: http://is.dal.ca/~huismans/publications.htm.

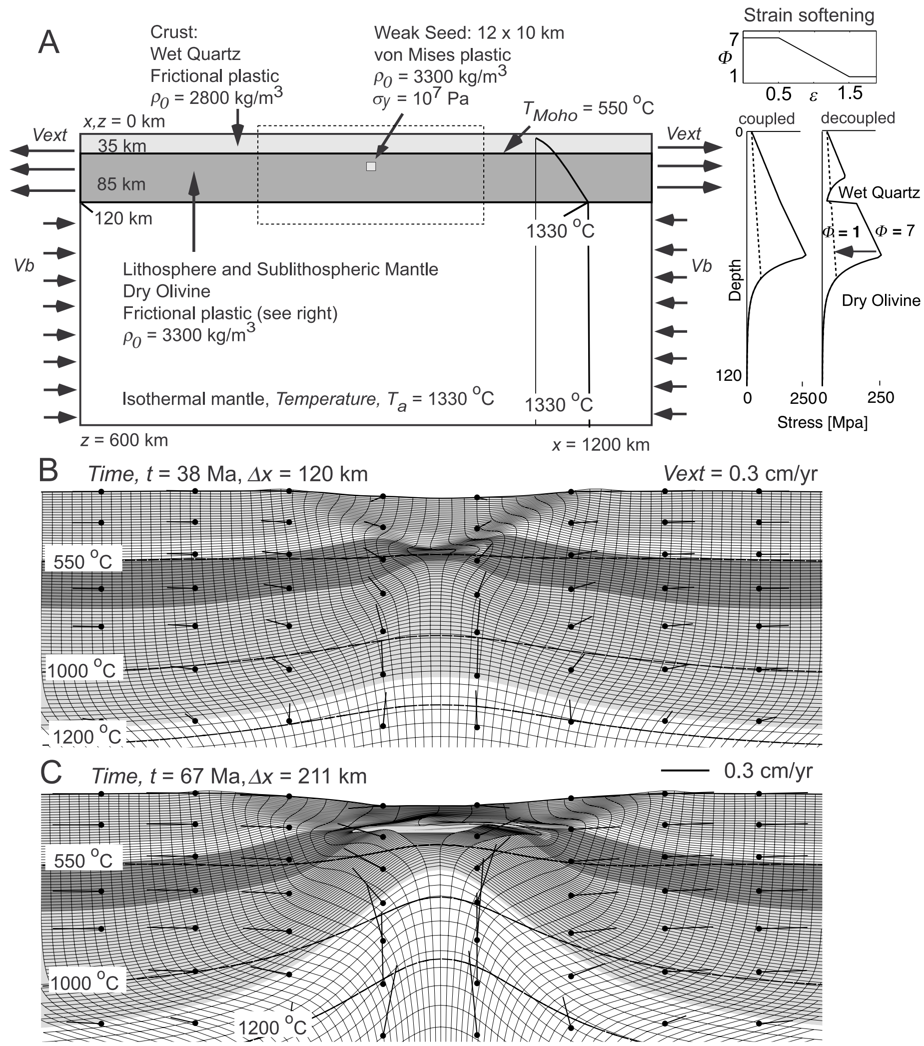
Figure 2. A, B: Coupled model 2 [η_{eff}(wet quartz x 100)], same as model 1 except with strain softening (see Fig. 1A), after extension of 75 and 135 km, respectively. Scaling of quartz viscosity makes upper three layers frictional plastic. Note asymmetric extension.

Figure 3. A, B: Decoupled model 3, same as model 2 except with [η_{eff}(wet quartz)], after extension of 75 and 135 km, respectively. No scaling of quartz viscosity makes lower crust ductile. Note weak early asymmetry followed by symmetric lithospheric mantle necking.

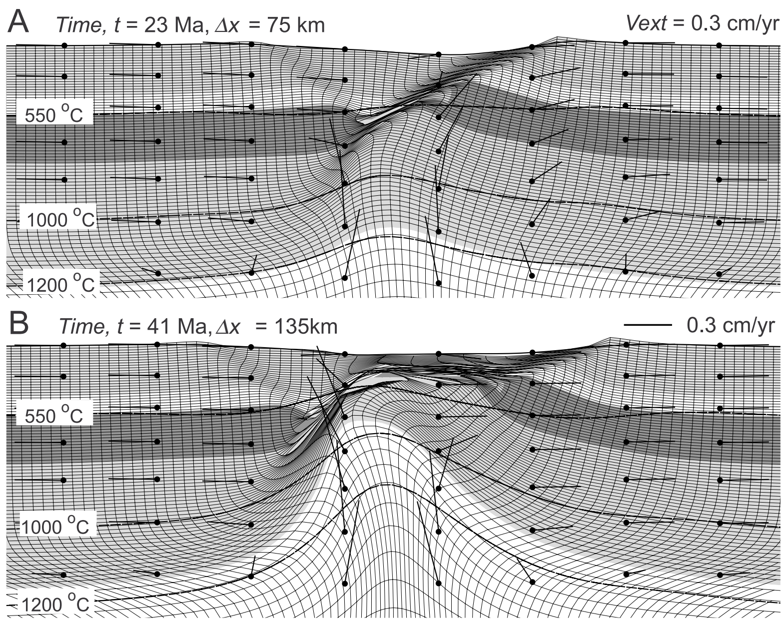
Figure 4. A, B: Coupled model 4 [η_{eff}(wet quartz x 100)], same as model 2 except rifting velocity increased to 30 cm/yr, after extension of 250 and 400 km, respectively. Scaling of quartz viscosity makes upper three layers frictional plastic. Increased rifting velocity causes return to symmetric style.

Figure 5. Summary of rifting modes seen in the model experiments and their relationship to rifting velocity and (coupled versus decoupled) frictional plastic and/or ductile control of model lithosphere. AA: fully asymmetric rifting of both layers; AS: asymmetric upper lithosphere rifting and symmetric lower lithosphere rifting; SS: fully symmetric rifting in both upper and lower lithosphere.

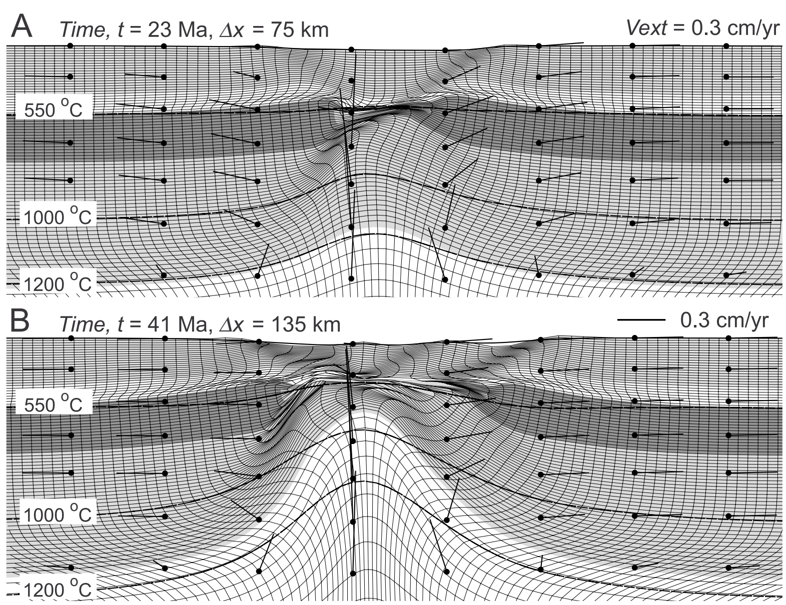
Huismans and Beaumont, Figure 1a,b,c



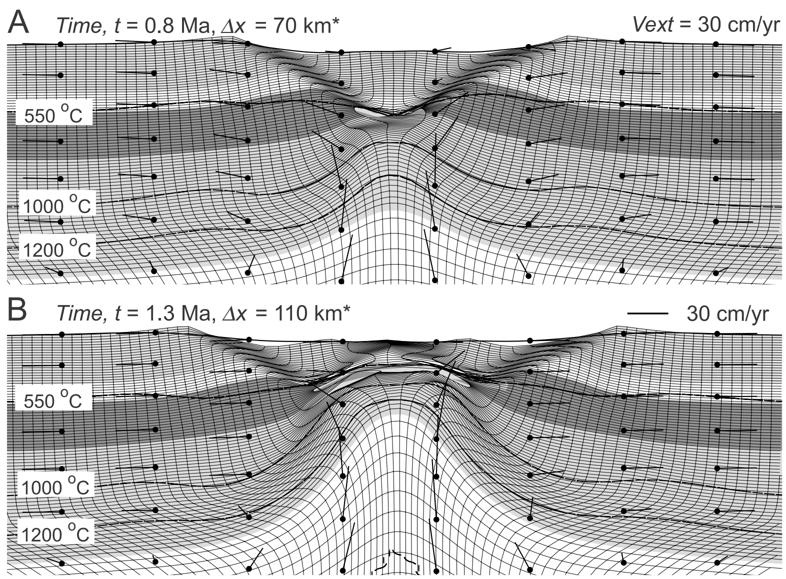
Huismans and Beaumont, Figure 2a,b



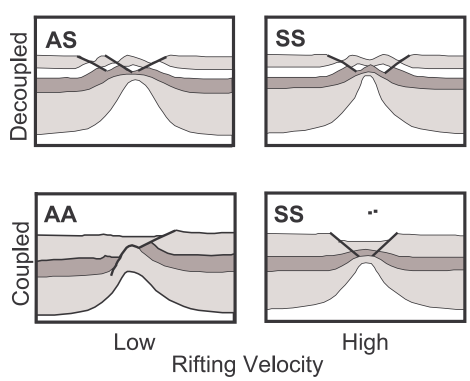
Huismans and Beaumont, Figure 3a,b



Huismans and Beaumont, Figure 4a,b



Huismans and Beaumont, Figure 5



APPENDIX 2: EXAMPLES OF PRELIMINARY NUMERICAL CALCULATIONS OF SALT TECTONICS

As an illustration of the potential capabilities of the current 2D Arbitrary-Lagrangian-Eulerian viscous-plastic finite element program (SOPALE), two sets of preliminary results are included that show the response to extension and contraction of a sedimentary basin containing a uniform layer of Newtonian 'salt', density 2100kg/m^3, overlain by frictional-plastic (Coulomb) overburden, density 2300kg/m^3, with an internal angle of friction of 10 degrees (representing somewhat overpressured sediments). The Eulerian model grid is uniform with 81 (vertical) x 801 (horizontal) nodes. Each element is 62.5x 250m. The models are purposely kept simple and no syn-kinematic sedimentation is included, although this can easily be added.

Extensional Models

E1-High Viscosity

The plane-strain vertical cross section model domain is initially 200km wide and 5km deep and contains the Coulomb material except for a 2km thick basal layer of 'salt' which extends from 10-190km representing a finite width salt basin. The 'salt' has an unrealistically high viscosity $5x10^{20}$ Pa.s (but see later models for lower values). Extension is driven by basal velocity boundary conditions that increase uniformly from 0-0.01cm/yr between 10 and 190 km, simulating very slow pure shear extension of the basement underlying the basin. Slow extension is required for this choice of viscosity to limit the stress levels to those anticipated for salt tectonics.

When there is no extension this model is stable even under quite large finite perturbations of the interface between the salt and the overburden because the finite strength of the Coulomb layer exceeds the buoyancy forces for this combination of layer thicknesses even with perturbations. That is, in a tectonically stable regime no active piercement driven solely by buoyancy forces will occur. This is, of course, quite different from Rayleigh-Taylor instabilities in purely viscous media. For example, were the overburden viscous, not Coulomb, the system would be intrinsically unstable. However, as recognized more than a decade ago the more difficult problem of salt diapirism into plastic overburden is most likely more comparable to the natural system in sedimentary basins.

The model evolution for a series of extensional increments (Figure 1, Δx (max)), shows the Lagrangian grid which gives a measure of the deformation for part of the basin, 0-90km. The overburden fails plastically, necks, and forms grabens beneath which the salt ponds as rollers which are asymmetric. There is a characteristic length scale for the rafts which occurs across the width of the basin, although all of the necks do not grow at the same rate. As the rafts of overburden extend the salt is withdrawn and rises as reactive and piercing diapiric salt walls. Later in the evolution there is further deformation within the rafts as the basal shear stress increases when the underlying salt thins. In places the grid lines have been removed for clarity and these white areas are the extended ends of the rafts. They will be better defined with a higher resolution Lagrangian grid. See Jackson and Vendeville (1994, Fig.4) for examples of salt walls in the Whale and Horseshoe basins, Newfoundland.

Variations on E1; E2-E5

Figure 2 shows the colour equivalent of Figure 1c from E1 for a series of models. This E1 frame is reproduced as Figure 2a. Model E2 (Figure 2b) is the same as E1 except that the overburden is half as thick, 1.5km, and the salt layer is 3.5km thick. The thickness change affects the characteristic length scale of the rafts and diapirism increases with respect to graben formation. Model E3 (Figure 2c) has a three layer overburden, layers 1 and 3 are Coulomb, respectively 1km and 1.5km thick. Layer 2 has the same viscosity as the 'salt' but the density is the same as the overburden and the layer is 0.5km thick. The result shows a more complex deformation pattern involving asymmetric detachment of the Coulomb layers, and the formation of grabens that are offset from the rafts of the lower Coulomb layer and the salt rollers. Salt diapirs pierce the upper layer later in the model evolution. This model merely demonstrates the increasing complexity of the model behaviour as the number of model layers increase. Models E4 and E5 (Figure 2d and e) are the same as model E1 except that the viscosity and extension rates are reduced and increased by factors of 100 (for E4) and 10 (for E5), respectively. The results show that with this scaling the results of E1, E4 and E5 are quite similar, though not identical, thereby demonstrating that models can be investigated for the 'salt' viscosity range $5x10^{20}$ to $5x10^{18}$ Pa s. This value could also be reduced by an additional order of magnitude.

Contraction Models

C1-High Viscosity

Model C1 is the same as E1 except that the salt basin is narrower, extending from 70-195km, and the pure shear basal boundary condition also extends across the same region but is now contractional from right to left with a maximum velocity of 0.01cm/yr. The model evolution (Figure 3) shows the region from 0-90km in which an allochthonous thin skinned fold-thrust belt forms from material expelled from the basin during inversion. The thrust belt takes the form of a critical Coulomb wedge of material with both an internal and basal angle of friction of 10 degrees (Figure 3b,c). There is some deformation of and accretion to the footwall. Later in the evolution (e.g. Figure 2d) viscous salt is intruded into the basal detachment/shear zone of the wedge. The overburden finally fails with synchronous piercement by a large diapiric salt wall (Figure 3e,f). The model shows the type of complexities to be expected in thin-skinned fold-thrust belts involving salt.

Variations on C1; C2-C5

Figure 4 is similar to Figure 2 in that it shows the results of a series of models, in this case for the contractional equivalents of the extensional models. The amounts of contraction (labelled Δx (max)) do, however, vary among the models. Figure 4a is the colour version of the last panel of Figure 3 and shows the high viscosity salt model overlain by an initially 3km thick Coulomb overburden. The colours clearly show the intrusion of the salt (blue) along the decollement and the large diapir. When the initial thickness of the overburden is reduced to 1.5km, model C2 (Figure 4b), proportionately more salt is laterally intruded and the wedge is correspondingly thinner and weaker. There are now three distinct diapirs. Although we have not analyzed the results, the evolution of the model stress field will allow us to determine the mode of failure of the wedge. Has it glided forward leaving extensional allochthons intruded by the salt, or is it still a compressional wedge with active piercement by the salt?

The results for model C3 in which the overburden has three layers (Figure 4c) are quite complex. The overburden is now characterized by folding and detachment instead of plastic plugs. This is more representative of the normal stratigraphic response of a layered sedimentary basin/wedge. Although the accuracy of a model like this must be tested by higher resolution calculations, the preliminary results give some indication of complicated deformation that can be predicted.

Figure 4d shows the result of model C4 which is the same as C1 except the convergence velocity is increased by a factor of 100 and the salt viscosity is reduced by the same factor. The results are similar to those of C1 as expected, until the buoyancy forces which have not been rescaled, begin to dominate and lead to the intrusion of a diapir in a different location.

Figure 4e shows both the basin and thrust belt parts of model C5 at a relatively early stage of convergence. This model is the same as C1 except that the velocity is increased by a factor of 10 and the salt viscosity is decreased by the same factor. The figure emphasizes the plug style of deformation of the thick Coulomb overburden with both pop-ups and pop-downs into the salt. The result contrasts strongly with that of three layer overburden, model C3, demonstrating that a composite containing thin ductile layers will 'fold' rather than fail as a series of plastic plugs.

Overall the preliminary results are encouraging. They provide some confidence that the salt tectonics component of the proposal is tractable and that there are a wealth of interesting interactions to be studied.

Research on the extensional models (E-type) has been refined this Summer by focusing on systematic comparison of the onset of the boudinage (necking) instability in the numerical models with the corresponding theory. The results are encouraging in regard to both the raft length scales at which the instability grows the fastest and the rate at which these instabilities grow for small perturbations. We have also started work on a comparison of the stability of frictional overburden above salt substratum (corresponding to progradation of a delta over a salt layer) and are comparing the numerical results with the corresponding approximate theory.

MODEL E1: Extensional Reactivation of Basin Containing Salt

Overburden: 3 km thick
Coulomb $\phi = 10^{o}$

Salt: 2km thick
$\eta = 5 \times 10^{20}$ Pa.s.

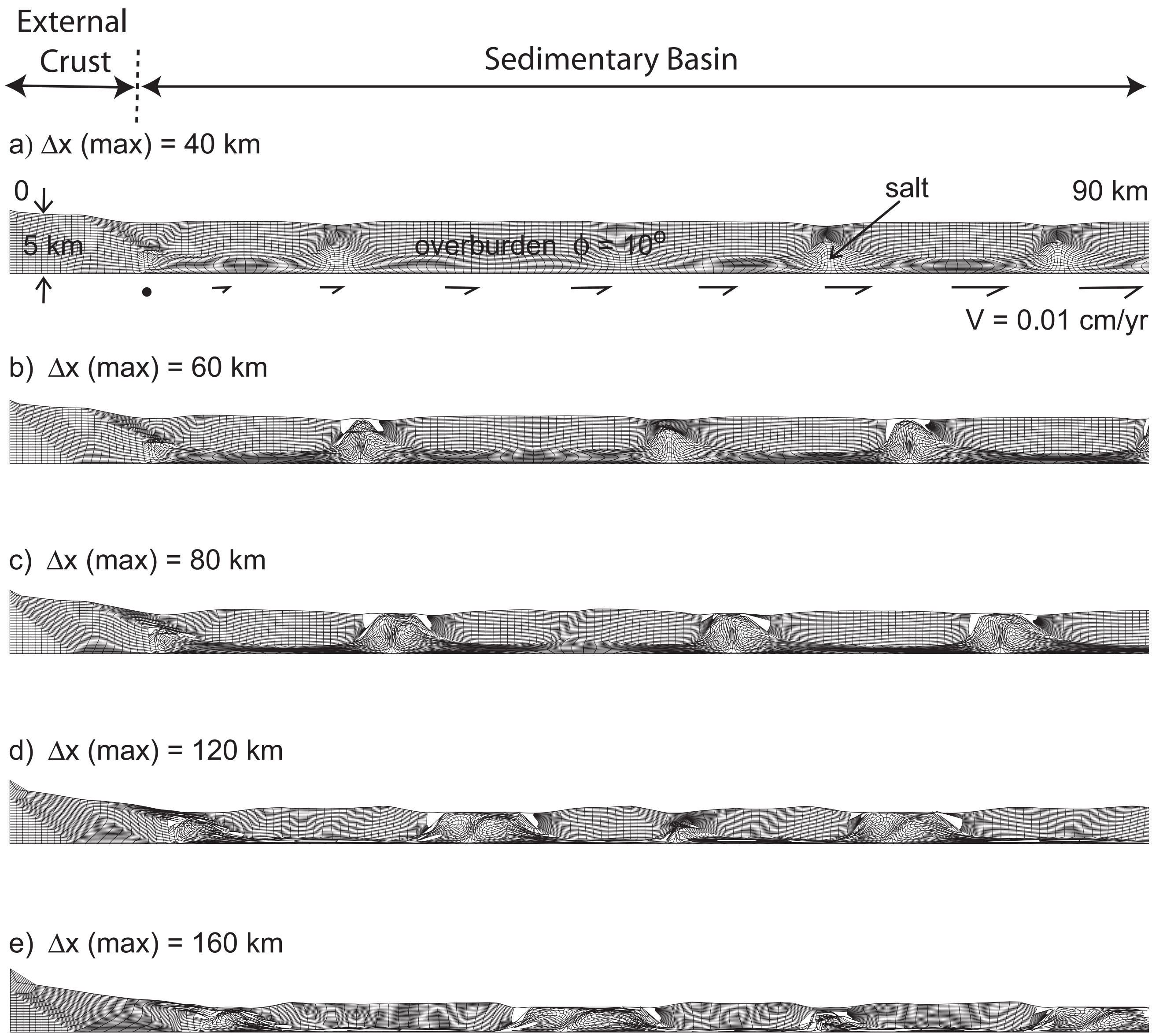
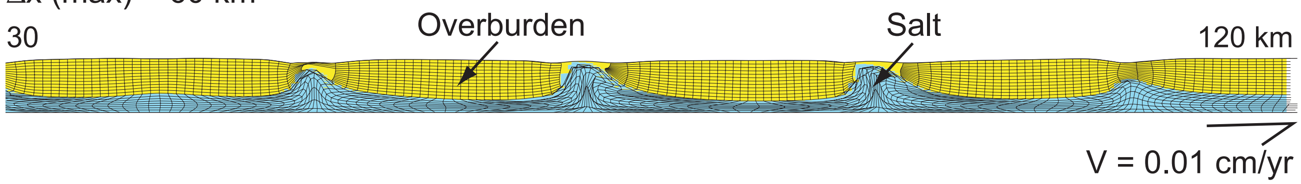


Figure A2.1

Styles of Models of Extensional Reactivation of Basins Containing Salt

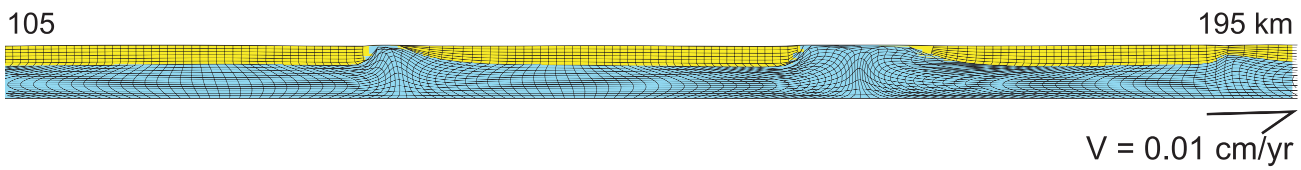
a) MODEL E1 Salt (2km, η = 5 x 10^{20} Pa.s.) Overburden (3 km, ϕ = 10^{o})

Δx (max) = 60 km



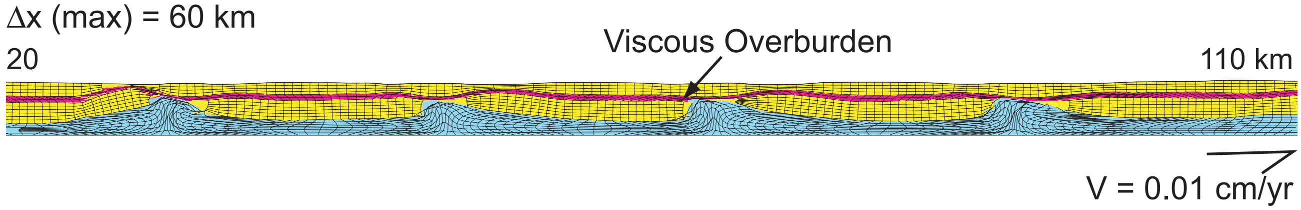
b) MODEL E2 Salt (3.5km, η = 5 x 10^{20} Pa.s.) Overburden (1.5 km, ϕ = 10^{o})

Δx (max) = 60 km



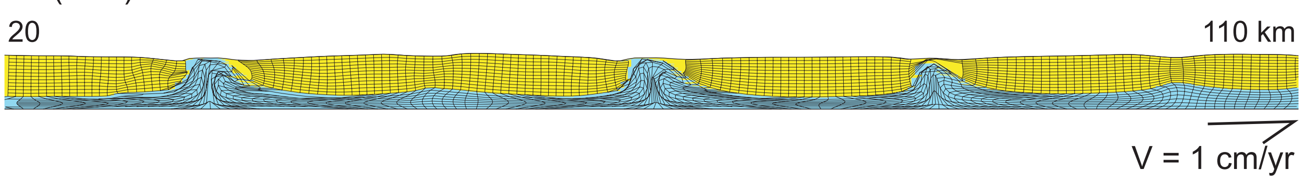
c) MODEL E3 Salt (2km, η = 5 x 10^{20} Pa.s.) Overburden (3 km, ϕ = 10^{o}, viscous, ϕ = 10^{o})

Δx (max) = 60 km



d) MODEL E4 Salt (2km, η = 5 x 10^{18} Pa.s.) Overburden (3 km, ϕ = 10^{o})

Δx (max) = 60 km



e) MODEL E5 Salt (2km, η = 5 x 10^{19} Pa.s.) Overburden (3 km, ϕ = 10^{o})

Δx (max) = 60 km

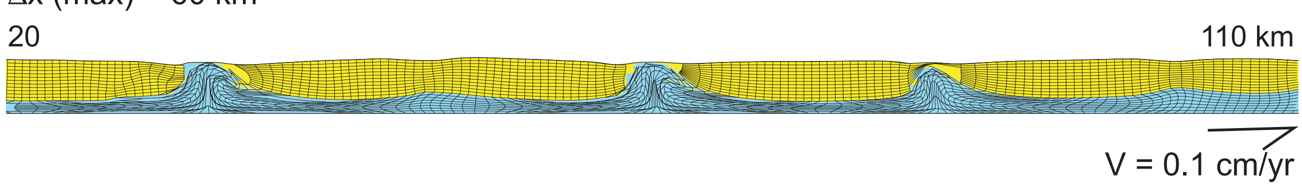


Figure A2.2

MODEL C1: Basin Inversion Creating Overthrust Containing Salt

Overburden: 3 km thick
Coulomb $\phi = 10^o$

Salt: 2km thick
$\eta = 5 \times 10^{20}$ Pa.s.

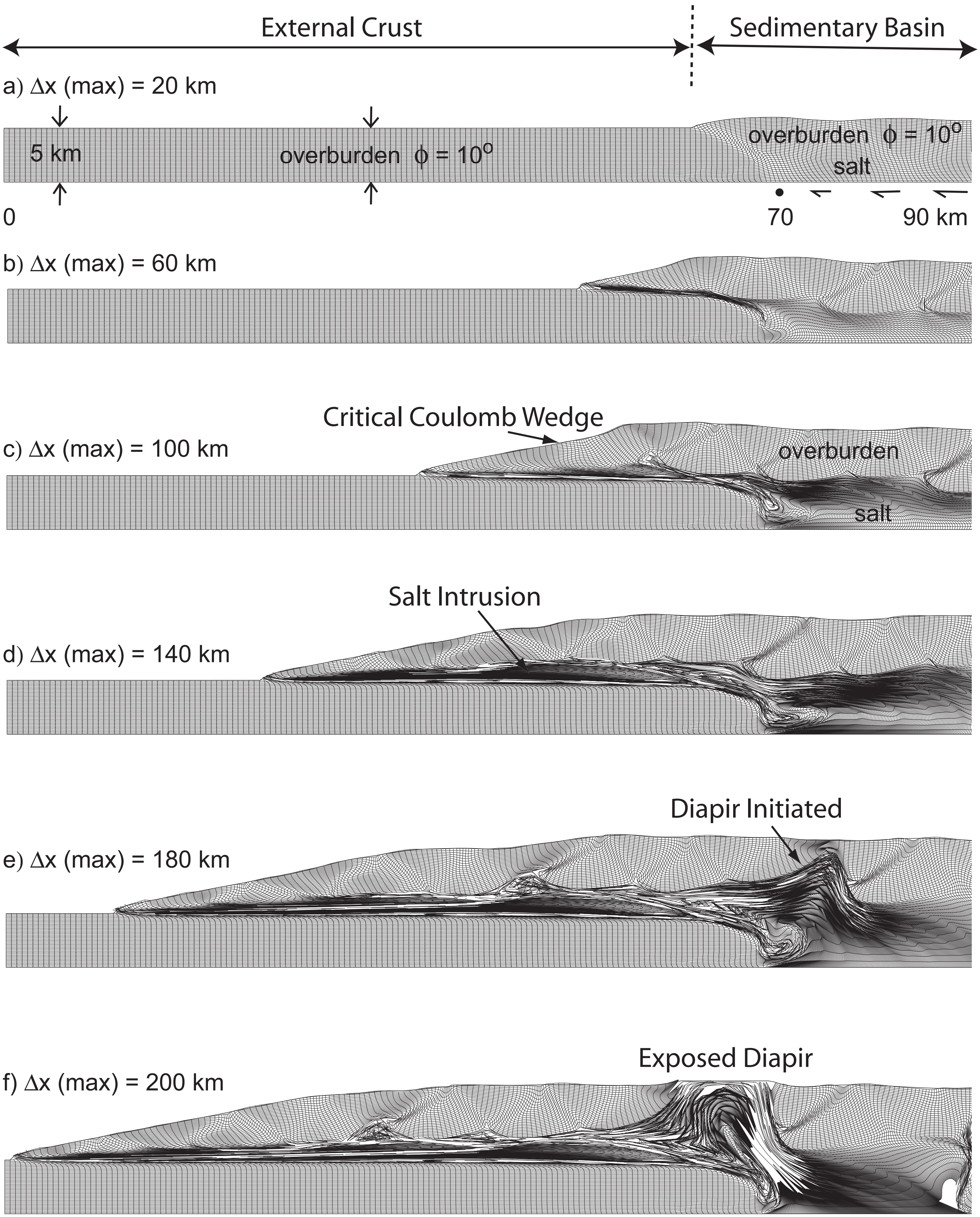


Figure A2.3

Styles of Models of Basin Inversion and Overthrust Wedges Containing Salt

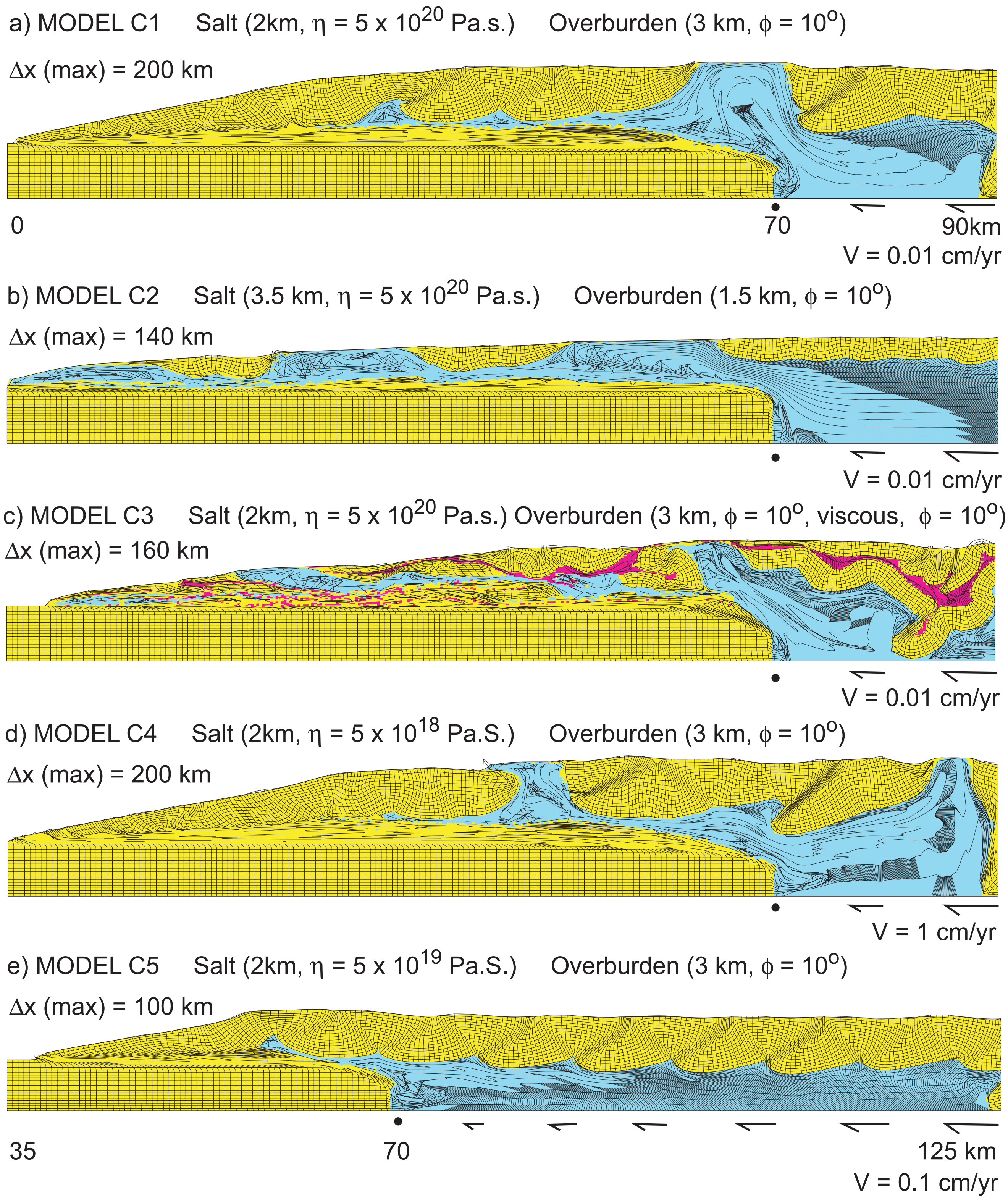


Figure A2.4