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Contract No. NRC–02–97–009
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U.S. Nuclear Regulatory Commission
ATTN: Dr. John S. Trapp, Program Manager
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Subject: Transmittal of revisions to CNWRA Intermediate Milestone 20.01402.461.155—Modeling Magma-Drift Interaction at the Proposed High-level Radioactive Waste Repository at Yucca Mountain, Nevada, USA

The authors have reviewed the NRC staff's required and suggested changes that were sent to Dr. Brittain Hill on May 7, 2001 regarding the subject milestone. Because of the potential importance of this paper, they have documented the disposition of required and suggested changes to this manuscript. These changes are made in strikeout-redline format on the original report in file 1402461_155b_red.wpd. A clean version of the revised report is provided in file 1402461_155b.wpd and in paper copy, along with a revised figure 4 in file 1402461_155b_f4.pdf. Changes to the subject report are summarized as follows:

1. page 5, Implications: Change the phrase "models are consistent with observations of explosive basaltic eruptions and current knowledge of the underlying physics" to "models are consistent with general observations of explosive basaltic eruptions." Agreed, wording changed to "...the models are consistent with general observations of explosive basaltic eruptions and current knowledge of the underlying physics." To address the staff's concern regarding case 3 flow pressures, the third paragraph in the **steady flow regime** section was changed to:

"... flow rates are somewhat smaller than in case 1, in which the magma flows along the dike to the surface (Fig 5b). Calculated flow pressures for case 3 clearly exceed the minimum fracture strength of the overlying rock. If a conduit formed initially in response to flow down a 4-km-long access drift, these large flow pressures would likely cause significant widening in the conduit geometry or the formation of additional conduits.
{new paragraph}
The flow calculations for cases 2 and 3 may be used ..."

The authors also have strengthened the arguments for the pressure necessary to dilate fractures at repository depths in reference [20] by adding this sentence to the end of the paragraph "This pressure range also

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corresponds to fluid pressures of 5.1–5.5 MPa for Yucca Mountain hydrofracturing stress measurements in Stock, J. M., Healy, J. H., Hickman, S. H., and Zoback, M. D., 1985, Journal of Geophysical Research, 90: 8691–8706."

2. Page 5, Implications: The text tends to imply that Case 3 is the correct model by stating: "models indicate that much of the repository will be quickly filled by magma." Reword to something like "models indicate that intersected drifts may be quickly filled by magma." Agreed, wording changed to "The models indicate that intersected drifts will be quickly filled by magma at an early stage in an eruption, with likely disruption of the drift contents."

3. Page 6, Implications: Remove the phrase "it remains to be determined if these consequences result in unacceptably high risk". It could be reworded to something like, "the consequences resulting from these models remains to be determine". Agreed, wording changed to "Although there are large uncertainties inherent in these conceptual models, the risk significance of these models should be determined for the proposed subsurface repository at Yucca Mountain."

4. Page 4, Steady Flow regime: The paper unnecessarily speculates on what might be done for human intrusion - remove the phrase "which would likely be blocked to prevent human intrusion into the repository," Agreed, wording changed to "Breakout from the access drift, which would likely be closed at each end [5], may occur at a variety of locations (e.g., structural weaknesses, ventilation shafts)."

5. Abstract and 1st paragraph of Introduction: The term "performance period" should be replaced with proposed compliance period. Agreed, wording changed to "...the proposed 10^4 yr compliance period..." in the abstract and "...10,000 yr, the proposed compliance period of the repository [2]..." in the introduction.

6. Introduction, 1st paragraph: In the introduction a reference to the proposed compliance period should be added directly after "period." Agreed. As in comment #5, reference [2] now is
2. Federal Register, 1999, Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada; Proposed Rule, 64(34) 8639–8679 (February 22, 1999), Washington, DC: Government Printing Office.

7. Introduction, 2nd paragraph: In the second paragraph of the introduction a better characterization of repository design needs to be included to better frame the discussion. Agreed, wording added to this paragraph to clarify initial assumptions: "...least resistance, and (d) interactions with other engineered components, such as ventilation shafts or drift supports, have minor effects on magma flow processes."

The NRC staff also had twelve suggestions for this report. The authors will need to discuss suggestions 1–3, to appropriately clarify the points raised by the staff. These discussions, however, cannot occur until the week of 21 May 2001 due to prior commitments by several of the authors.

4. Abstract; 5[th] line: change "ascending magma will be diverted" to "ascending magma can be diverted" The authors believe the sentence is accurate as written, as magma flow is predicated on dike intersection. The authors conclude there is sufficient information to conclude that magma has a fluid pressure that exceeds lithostatic confining pressure. If pressurized magma intersects a drift that is under 0.01 MPa pressure, the >4–7 MPa magma will flow into the drift. The authors will need additional information from NRC staff to indicate how magma flow is a conditional event given this large pressure differential. The introduction also states that this report does not consider dike deflection due to thermo-mechanical effects (e.g., AMR Dike Propagation Near Drifts).

Staff suggestion #5 was not supplied in the May 7, 2001 letter.

6. Page 5, Implications; 6[th] line: Change "with disruption of the contents" to "with potential disruption of the contents." Agreed, wording changed to "The models indicate that intersected drifts will be quickly filled by magma at an early stage in an eruption, with potential disruption of the drift contents."

7. Page 4; last paragraph: In describing figure 4a-c, the text clearly identifies the area for Case 2 while the area for Case 1 is not provided and a second sentence apparently provides the area for Case 3. It would help to clarify the areas use and if the assumed area has a significant impact on the pressures observed in the calculations it may require a sentence or two to explain. This is something that would most likely come up in future discussions with DOE.
Agreed, wording changed to "... (figure 4a–c): (Case 1) that the deep dike path continues to the surface without any major perturbation by the repository system, (Case 2) that the pathway to the surface is shifted to a new position, 500 m along a drift with an area of 20 m^2, and (Case 3) that the magma uses the main access drift to the repository for flow to the surface. This access drift is taken to be 4 km long, with a gentle incline to the surface and a drift area of 50 m^2. Breakout..."

8. Figure 3a-: This figure is confusing. It would be very helpful to somewhere state where the X distance is measured for the dike and for the drift. In addition, different styles of lines for i-v should be used so that the cases can be followed in both the left and right portions of the figures. and
11. Figure 3: As reading left to right in the figure the dike (left) comes before the drift (right), the caption should read "position along the dike and drift" not "position along the drift and dike" The authors agree that figure 3 should be clarified, as few readers have seen the Bokhove and Woods (JGR) paper. This figure will be modified by the appropriate authors.

9. Page 4; 3[rd] paragraph: change "In additional to" to "In addition to" Agreed, wording corrected as suggested.

10. Reference 14: The year of publication for Stasiuk, Jaupart and Sparks reference is missing. Agreed, 1993 publication date added to reference.

12. Page 4, second paragraph, first sentence: Change the order to dike-drift from drift-dike system to be consistent with recommendation 1. Agreed, wording changed as suggested.

13. Reference 8: Suggest that the following be added at the end of the citation. "In addition, a drift used for ventilation purposes would be beneath all emplacement drift and would be connected to each emplacement drift." Agreed, reference 8 now reads "... The design has not yet been finalized so, for example, the drift ends could be closed or open to the access drifts. In addition, a ventilation drift may be located beneath and connected to the waste emplacement drifts."

The authors will discuss suggestions #1–3, 8, and 11 as soon as they are able. Dr. Hill will discuss with you any additional changes to this report that may arise from these discussions, and will provide an updated report to you if necessary. The authors will wait to submit this report to the journal Science until they receive formal approval from the NRC of the revised report.

The authors thank the NRC staff for the detailed reviews they have given this paper. They believe it would be appropriate to add their names to the list of reviewers in reference 22, as they have helped to clarify and focus the important results of this paper. Please forward their names to Dr. Hill so their contribution can be acknowledged. If you have further questions about this revised report, please contact Dr. Brittain Hill at (210) 522-6087 or me at (210) 522-5183.

Sincerely yours,

H. Lawrence McKague

Dr. H. Lawrence McKague
Element Manager, GLGP

HLM/rae

Enclosures

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Modeling Magma-Drift Interaction at the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, Nevada, USA

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May 9, 2001

Abstract

We examine the ascent of alkali basalt magma containing 2 wt percent water through a dike and into a horizontal subsurface drift as part of a risk assessment for the proposed high-level radioactive waste repository beneath Yucca Mountain, Nevada, USA. The probability of such an event is estimated to be 10^{-8}–10^{-7}/yr for the proposed 10^4 yr compliance period of the repository. On intersection of the dike with the low pressure, horizontal drift, the ascending magma will be diverted into the drift. The fragmenting mixture expands down the drift to reach speeds of order 100–300 m/s. After this initial disruptive activity, parts of the repository can be filled with magma within a matter of hours until a pathway is found to allow the magma to vent. Magma flow through the drift network will cause intense heating of any waste canisters located along the pathway between the dike and the surface conduit. The assessments suggest a greater number of waste packages may be adversely affected than previously recognized.

Introduction

Increasingly, geologists and geophysicists are called upon to develop and use models of geophysical processes to evaluate volcanic hazard and risk. This is particularly evident for the siting of nuclear facilities, which must be located in areas of very low geologic risk [*1*]. Because of the requirement to assure long-term public health and safety, risk assessments are made for rare phenomena, such as volcanic eruptions, which require development of realistic physical models. A striking example is the need to model the impact of volcanic activity on the proposed high-level radioactive waste repository beneath Yucca Mountain, Nevada, USA. Probabilistic volcanic hazard assessments indicate that the likelihood of a basaltic volcanic eruption occurring in the repository during the next 10,000 yr, the proposed compliance period of the repository [*2*], is 10^{-8}–10^{-7} per year [*3*]. This hazard is sufficient to require that the potential impact of volcanic activity on repository performance be evaluated [*2*].

Any assessment involves evaluating the interaction of natural volcanic processes with a complex engineered system. Large uncertainties in the assessment are related to variations in engineering

design, natural variations in the geologic system, and epistemic uncertainty in the mechanisms of basalt eruption. Here we develop a model of magma intrusion and flow into the repository. We consider the initial transient flows that occur when magma first intersects repository drifts, and then longer-term steady-state flows that develop once eruptive pathways to the surface have been established. Three alternative scenarios for effects of the repository on pathway development are postulated and discussed. In a basaltic eruption lasting several days or weeks the interactions between moving magma and the waste canisters will control the amount of radioactive waste ultimately released. These three scenarios are predicated on the assumptions that: (a) tangential and thermal stresses around the drift do not prevent dike intersection with the drifts; (b) the drifts are not back-filled with sufficient material to impede flow; (c) following intersection of the dike with the drift, the magma will be diverted into the drift, because the drift provides the path of least resistance, and (d) interactions with other engineered components, such as ventilation shafts or drift supports, have minor effects on magma flow processes. While further studies are being conducted to test these assumptions, our current assessments suggest a greater number of waste packages may be adversely affected than previously recognized [*4,5*].

Volcanic hazards at the proposed repository site result from its location within a geologically active basaltic volcanic field. Six Quaternary pyroclastic basaltic volcanoes are located within 20 km of the site (Figure 1), including Lathrop Wells volcano, formed by eruptions approximately 80 ka [*6*]. These mildly alkaline cinder cones are characterized by relatively wet basaltic magmas, with olivine and amphibole assemblages indicating about 2 wt percent water in the magma [*7*]. Such magmas produce relatively small volume (~0.1 km^3) but explosive eruptions [*8,9*], which may have substantial impact on waste packages stored in the subsurface repository drifts.

In the proposed design [*10*], repository drifts would be located 200–300 m below the surface and have a cross-sectional area of order 20 m^2. Given the roughly E-W trend of the repository drifts [*5, 11*] and NNE trend of maximum horizontal compressional stress [*12*], magma ascending beneath the repository is expected to form a dike that cuts across numerous drifts. Each intersected drift will drain magma from a section of the dike of order 80 m in length (Figure 2), corresponding to the drift spacing. The drifts may accommodate a large fraction of the ascending magma, as the cross-sectional area of each drift equals that of a 20 m section of a dike, 1 m wide. Prior to magma intrusion, the drifts will have pressure close to atmospheric [*13*] and the magma in the dike will have a pressure of order 10 MPa. Therefore, on intersection with the drift, there will be a very rapid decompression of the magma. If the alkali basalt contains a typical amount of water, of order 2 wt percent, this decompression will be explosive [*14*].

Physical and Mathematical Modeling

We present a series of flow models assuming a simple geometry for the dike-drift system (Figure 2). As a consequence of magma decompression and volatile exsolution, the magma in both the dike and the drift will expand and accelerate. The magma may then break up to produce a high speed mixture of vesicular fragments of magma and gas in regions of low pressure (*e.g.*, near the Earth's surface or on encountering an empty drift). This flow speed typically can be

very high and may exceed the slip velocity between the gas and many of the finer liquid fragments. As a first quantitative model, we examine the possible magnitude of such a flow, when the magma in the dike first intersects the drift. We examine the intensity of a homogeneous flow with liquid, particles and gas moving at the same speed. We also assume the dike and drift walls exert a viscous and turbulent drag on the flow [9]. The motion may be described by the averaged speed u and density ρ in terms of position x and time t along the drift or dike, leading to the equation for momentum conservation,

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}\right)=-\frac{\partial p}{\partial x}-fu-\rho g H(x), \tag{1}$$

where $H(x)$ has value 1 in the vertical dike, and value 0 in the horizontal drift. Here, f is the drag coefficient, which has value $f=\dfrac{\alpha\mu}{d^2}+\dfrac{2C\rho\mu}{d}$, where the viscosity μ=10 Pa s, α = 12 and 8 for flow in the dike and cylindrical drift, d denotes the dike width or drift radius, and C denotes the turbulent drag coefficient, which depends on the wall roughness, but which is taken to have the representative value 0.01. We couple equation (1) with the equation for conservation of mass in the dike or drift, with cross-sectional area $A(x)$,

$$\frac{\partial(A(x)\rho)}{\partial t}+\frac{\partial(A(x)\rho\mu)}{\partial x}=0. \tag{2}$$

The model is completed with an equation describing the bulk density of the magma-gas mixture: where n is the dissolved gas mass fraction, which decreases with pressure according to the solubility law

$$n=n_0-sp^{1/2}, \tag{3}$$

where the solubility coefficient s has value 3×10^{-6} Pa$^{-1/2}$ and n_o is the total gas mass fraction [15]. For this process, we assume that the mixture remains isothermal owing to the large thermal inertia of the liquid phase.

The cross-sectional area of the dike or drift, given by the function $A(x)$, is assumed to vary smoothly from the dike cross-section to that of the drift over a distance of 5 m around the point of intersection of the dike and the drift. This provides a parameterized model of the three-dimensional flow at the dike-drift intersection using the stream-tube approach. The model system of equations has been solved numerically. Shock-capturing second- and third-order Local Lax Friedrich and Essentially Non-Oscillatory numerical schemes have been used and tested extensively for accuracy [16].

Model Calculations

We assume that the magma originates at a depth of around 30 km at the base of the crust and has an unvesiculated density of 2600 kg/m^3. The crustal section is assumed to have a linear density variation from 2940 kg/m^3 at the base to 2400 kg/m^3 at the surface [*17*]. The mean density contrast between magma and crust is thus 70 kg/m^3, resulting in a net buoyancy to drive the dense basaltic magma through the lower density rocks in the upper ten kilometers of the crust. In these circumstances the dike has the local lithostatic pressure plus an overpressure of order 10–20 MPa, which is easily sufficient for propagation of the dike tip into the crust [*17, 18*]. Apart from the waste canisters, the drift is assumed to be empty, and since the drift cross-sectional area is much larger than that of a 1.8-m-diameter canister, $A(x)$ is taken to be the total drift cross-sectional area in equation 2. The pressure in the drift is taken as being close to atmospheric, because the drift will be connected to the surface through a network of access drifts [*10*]. Repository drifts are assumed to be free of natural or artificial backfill. We also assume that the dike remains open after breaking through into the drift, so that magma continues to rise into and flow along the drift. These simplifications lead to an upper bound on the magnitude of flow in the drift, since in this model we assume that resistance in the dike is minimum.

Figures 3a,b indicate the evolution of velocity and pressure in the dike-drift system over the first ~10 s following break-through into the drift. Initially, there is a rapid expansion of the magma-volatile mixture as a rarefaction wave propagates back into the dike through the magma, and volatiles are exsolved. This expanding mixture accelerates along the drift reaching speeds of tens to hundreds of meters per second. Air is displaced and compressed ahead of the magma-volatile mixture and as a result, a shock forms in the air and moves down the drift at speeds of several hundreds of meters per second (curve i, Figures 3a,b). The subsequent flow behavior depends on whether the drift is closed at both ends or open at one end to a larger diameter access drift. If closed, then on reaching the end of the drift, the shock is reflected and its amplitude increases by a factor of order 10–20. The shock then propagates back upstream, moving into the magma-volatile mixture and back towards the dike at speeds of 20–30 m/s. As the shock moves through the magma-volatile mixture, the mixture is recompressed. A region of very high pressure, of order 10–20 MPa, develops between the end of the drift and the shock (curves ii–v, Figures 3a,b). These calculations suggest that, if the dike intersects the drift 200–300 m from the end of a closed drift, then the pressure will build up to this level along the whole drift, within about 10 s [*16*].

Alternatively, in an open-ended drift, the explosively erupting magma will begin to fill the access drift as well as the drifts it has directly intersected. After a period of a few hours the available underground space will be filled and the magma pressure in the repository will increase towards values comparable to the driving pressure [*19*]. In addition to initial fracture propagation ahead of the dike, development of large magma pressures in the repository or individual drifts could drive open a fracture in the overlying crust and produce a conduit to the surface for the erupting magma. Calculated estimates of the fluid pressure required to initiate a vertical fracture range from 2–6 MPa, depending upon the fracture orientation [*20*]. Hydrofracturing stress measurements, in borehole G-1 at Yucca Mountain, indicate pressures of 5.1–5.5 MPa are required to reopen existing fractures in the unsaturated zone near proposed repository depths at

Yucca Mountain [20].

Steady Flow Regime

The precise location of the preferred magma pathways from the drift to the surface will depend on many factors, including any heterogeneity or fractures in the overlying rock strata, proximity of the drift to the surface, and any damage to the rock prior to intersection of the dike and the drift. Since we have no basis for preferring a particular pathway, we compare three different cases which might bound the range of possibilities (figure 4a–c): (Case 1) that the deep dike path continues to the surface without any major perturbation by the repository system, (Case 2) that the pathway to the surface is shifted to a new position, 500 m along a drift with an area of 20 m^2, and (Case 3) that the magma uses the main access drift to the repository for flow to the surface. This access drift is taken to be 4 km long, with a gentle incline to the surface and a drift area of 50 m^2. Breakout from the access drift, which would likely be closed at each end [5], may occur at a variety of locations (e.g., structural weaknesses, ventilation shafts).

Once a flow path to the surface develops, a quasi-steady eruption will become established (figure 4a–c). In order to quantify the potential impact of such a steady flow regime on the canisters, we have extended the model, described by equations (1–3), to include a conduit from the drift to the surface. We then calculated steady flow solutions for the three different cases, assuming magma is supplied to the dike from a reservoir located 30 km below the surface. To complete the model, we apply the condition of choked flow as the magma-volatile mixture erupts at the surface [9]. Figures 5a,b illustrate the variation of velocity and pressure as the magma-volatile mixture rises from the dike, into the drift, and finally accelerates up the conduit to the surface.

In each case, we find eruption speeds of order 90 m/s. For flow limited to the dike (case 1), the pressure falls below lithostatic except near the exit to the surface, where the flow accelerates and expands so as to reach choked conditions. We find that in the case in which the flow is diverted along a drift, the flow pressure is elevated relative to lithostatic in the upper kilometer or so, in order to drive the flow along the drift (case 2) and main drift (case 3) towards the surface. As a result, the flow rates are somewhat smaller than in case 1, in which the magma flows along the dike to the surface (Fig 5b). Calculated flow pressures for case 3 clearly exceed the minimum fracture strength of the overlying rock [20]. If a conduit formed initially in response to flow down a 4-km-long access drift, these large flow pressures would likely cause significant widening in the conduit geometry or the formation of additional conduits.

The flow calculations for cases 2 and 3 may be used to estimate the drag force acting on the waste canisters in the drift, $\rho C_d u^2 A_c$, where A_c is the area of the end face of the canister and $C_d \sim 1$ is the drag coefficient of a canister. We find that for the above model flow calculations, the ratio of drag force to canister weight is typically of order or smaller than 0.1–1.0. This suggests that the canisters may be displaced down the drift, although the flow is much too weak to keep the canisters in suspension and any canister motion is likely to be relatively slow.

As well as mechanical damage, waste canisters will experience considerable thermal stress from the magma. For example, if the steady-flow regime becomes established, then the heat transfer from the molten magma to the containers will eventually lead to ductile deformation of the containers [*21*]. If we assume that the magma flows past the canisters with steady speed of order 10 m/s, as indicated in figure 5b, then the canister will gradually heat by thermal conduction from this quasi-steady magmatic heat source. To good approximation, the time-scale required to heat the 7 cm walls of the canister above a likely deformation temperature of 800 °C [*11*] is given by the time for thermal diffusion $d^2/\kappa \sim 10^3$ s, where the effective thermal diffusivity of the composite shell of the canister, $\kappa \sim 10^{-6}$ m^2/s. For times greater than ~ 10^3 s, the canisters will become deformable, and may then break open. The time required for thermal damage is short relative to the duration of most basaltic eruptions, and so canister failure is anticipated [*5, 11, 21*].

Implications

Our calculations point to the potential damage that an alkali basaltic volcanic eruption might have on the proposed subsurface repository at Yucca Mountain. Although our models are a considerable simplification of the complex processes involved with magma-repository interaction, the models are consistent with general observations of explosive basaltic eruptions and current knowledge of the underlying physics. The models indicate that intersected drifts will be quickly filled by magma at an early stage in an eruption, with potential disruption of the drift contents. The repository drifts may then provide a potential flow path to the surface. These results indicate that, although magma injection is a very low probability event, it can potentially affect a large number of waste canisters in the proposed repository. Heating of the waste packages is expected to lead to their failure, and prolonged magma flow through the repository drifts over periods of days to months may then provide a mechanism to transport contaminants to the Earth's surface. Although there are large uncertainties inherent in these conceptual models, the risk significance of these models should be determined for the proposed subsurface repository at Yucca Mountain. Important areas for future work include investigation of the effects of magma-volatile separation, especially in the repository drifts, mechanisms for waste package disaggregation and waste entrainment, and the coupling between magma flow and the evolution of the dike, drift, and conduit geometry [22].

References

1. International Atomic Energy Agency, 1997, *Volcanoes and Associated Topics in Relation to Nuclear Power Plant Siting,* Provisional Safety Standards Series No. 1, Vienna, Austria: International Atomic Energy Agency, 49 pp. International Atomic Energy Agency, 1986, *Principles for Limiting Releases of Radioactive Effluents into the Environment:* Safety Series No.77, Vienna, Austria: International Atomic Energy Agency, 32 pp. U.S. National Research Council, 1995, *Technical Bases for Yucca Mountain Standards,* Washington, DC: National Academy Press, 205 pp.

2. Federal Register, 1999, *Disposal of High-Level Radioactive Wastes in a Proposed Geological*

Repository at Yucca Mountain, Nevada; Proposed Rule, 64(34) 8639–8679, (February 22, 1999), Washington, DC: Government Printing Office.

3. Connor, C.B., Stamatakos, J.A., Ferrill, D.A., Hill, B.E., Ofoegbu, G.I., Conway, F.M., Sagar, B., and Trapp, J., 2000, Journal of Geophysical Research, 105: 417–432.

4. U.S. Nuclear Regulatory Commission, 1999, *Issue Resolution Status Report, Key Technical Issue: Igneous Activity*, Washington, DC: U.S. Nuclear Regulatory Commission, Office of Nuclear Safety and Safeguards, Division of Waste Management. Models in this report and [5] assume 1–30 waste canisters are disrupted directly during a basaltic volcanic eruption. These models correspond to case 1, in which subvolcanic conduit development is unaffected by the presence of subsurface drifts. Preliminary designs for the proposed repository have about 150 waste canisters in each of about 50 drifts.

5. Office of Civilian Waste Management System Management and Operating Contractor, 2000, *Total System Performance Assessment for the Site Recommendation*, TDR-WIS-PA-00001 REV 00 ICN 1, Las Vegas: NV, U.S. Department of Energy, Yucca Mountain Site Characterization Office, 787 pp.

6. Heizler, M.T., Perry, F.V., Crowe, B.M., Peters, L., and Appelt, R., 1999, Journal of Geophysical Research 104: 767–804.

7. Alkali basaltic lavas generally have elevated water contents (~1–3 wt %) relative to tholeiitic basalts erupted at ocean ridges and at Hawaii. The higher water contents reflect factors such as lower degrees of partial mantle melting that results in concentration of incompatible elements such as water, involvement of hydrous phases such as amphibole and phlogopite in melt generation (e.g., Vaniman, D.T., Crowe, B.M., and Gladney, E.S., 1981, Contributions to Mineralogy and Petrology, 80: 341–357.), and further concentration of water during differentiation. The Crater Flat alkali basalt, for example, contains titanpargasite crystals, indicating water pressures of tens of MPa and water contents in excess of 2 wt % (e.g., Knutson, J., and Green, T.H., 1975, Contributions to Mineralogy and Petrology, 52: 121–132).

8. Doubik, P., and Hill, B.E., 1999, Journal of Volcanology and Geothermal Research, 91: 43–64.

9. Wilson, L. and Head, J., 1981, Journal of Geophysical Research 86: 2971–3001.

10. The current repository design involves a series of 5-m-diameter and 1-km-long drifts spaced 80-m apart in an approximately east-west orientation. These drifts will be connected to access drifts of larger diameter (7–10 m) at one or both ends. The design has not yet been finalized so, for example, the drift ends could be closed or open to the access drifts. In addition, a ventilation drift may be located beneath and connected to the waste emplacement drifts.

11. Civilian Radioactive Waste Management System, Management and Operating Contractor,

2000, *Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations, Volume II: Postclosure Safety Strategy*, TDRL-WIS-RL-000001, Revision 04 ICN 01, Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor, 133 p. U.S. Department of Energy 1998, *Viability Assessment of a Repository at Yucca Mountain, Volume 3: Total System Performance Assessment*, DOE/RW-0508, Washington, DC: U.S. Department of Energy, Office of Civilian Radioactive Waste Management, 463 p.

12. Ferrill, D.A., Stamatakos, J.A., and Sims, D., 1999, Journal of Structural Geology, 21: 1027–1038.

13. U.S. Geological Survey, 1998, *Hydrogeology of the Unsaturated Zone, North Ramp area of the Exploratory Studies Facility, Yucca Mountain, Nevada*, Water-Resources Investigations Report 98-4050.

14. Relative to tholeiites, alkali basalts are quite explosive and substantial proportions of the magma are erupted in pyroclastic processes to form cinder cones. Activity is characterized by strombolian to violent strombolian activity with ejecta speeds of 100 to 200 m/s and fire fountains hundreds of metres high, as exemplified by the 0.2 km^3 alkali basalt eruption at Heimaey, Iceland in 1973 (Blackburn, E.A., Wilson, L., and Sparks, R.S.J., 1976, Journal of the Geological Society of London, 132: 429–440). Partial degassing of the dike tip may initially impede development of the explosive decompression, depending on the thickness of the degassed region at the dike tip and the dike ascent velocity.

15. Holloway, J.R. and Blank, J.G., 1994, *Application of experimental results to C-O-H species in Natural Melts, Ch 6*, in Volatiles in Magmas, Eds. M.R. Carroll and J.R. Holloway, Reviews in Mineralogy, Vol 30, Washington, DC: Mineralogical Society of America.

16. Bokhove, O., and Woods, A.W., 2001, The explosive decompression of basaltic magma into a sub-surface repository. sub-judice, Journal of Geophysical Research. This manuscript includes a detailed verification of the model through direct comparison with some exact analytic solutions for some simplified flow regimes.

17. The crustal densities chosen are consistent with seismic data in the region and the occurrence of Tertiary volcanic rocks and carbonates which make up the shallow crust in the Yucca Mountain area (e.g., [*4*]). A magma derived from 30 km depth in the continental lithosphere can easily generate a driving pressure of 10–20 MPa with a density deficiency of a few tens of kg/m^3 compared to the average density of the overlying lithosphere. Estimates of driving pressure for volcanic eruptions are also typically in the 10–20 MPa range (e.g., Stasiuk, M.V., Jaupart, C., and Sparks, R.S.J., 1993, Earth and Planetary Science Letters, 114: 505–516.)

18. Lister, J.R. and Kerr, R.C., 1991, Journal of Geophysical Research, 96: 10,049–10,077.

19. The volume of basalt erupted by < 5 Ma Yucca Mountain region cinder cones (10^7–10^8 m^3) is

much larger than the proposed repository volume (~10^6 m^3). For a dike of order 1 m width and 0.1–1 km length, and typical magma ascent speed of order 1 m/s, the eruption rate is typically 10^2 to 10^3 m^3/s. Thus, a repository can be completely filled with magma in only a few hours of the onset of an eruption.

20. Fluid pressures required to initiate vertical fracturing above the drift and upward propagation of magma are estimated using the Kirsch solution for rock hydrofracturing (e.g., Goodman, R.E., 1980, *Rock Mechanics*, New York, NY: John Wiley and Sons), and vary from 0–9 MPa, depending on drift orientation. The magma driving pressures required to open a conduit to the surface along the length of the drift can be estimated: $\frac{t}{l} = \frac{(P-S)}{G/(1-\nu)}$, where: t is the dike thickness, l is the dike length (in this case equal to the length of the drift), $P-S$ is the driving pressure, G is the shear modulus, and ν is Poisson's ratio (Pollard, D.D., 1987, *Elementary fracture mechanics applied to the structural interpretation of dykes*, in H.C. Hall and W.F. Fahrig, eds., Mafic Dyke Swarms, Geologic Association of Canada Special Paper 34, St. Johns, Newfoundland: Geologic Association of Canada, p. 5–24). Using a drift length of 1 km, $G = 10^3$ MPa, and $n = 0.25$. For a 1-m-wide dike to propagate to the surface, the driving pressure $(P-S) = 1.3$ MPa. This result is highly dependent on the value of G, which could be as high as 10^4 MPa, indicating that 1 MPa $< (P-S) <$10 MPa. This suggests that a fluid pressure of at least 2–3 MPa is needed to form a 1-m-wide dike along the length of the drift trending perpendicular to the least horizontal compressive stress and at least 5–6 MPa is needed to form a 1-m-wide dike along the length of the drift trending perpendicular to the maximum horizontal compressive stress. This pressure range also corresponds to fluid pressures of 5.1–5.5 MPa for Yucca Mountain hydrofracturing stress measurements in Stock, J. M., Healy, J. H., Hickman, S. H., and Zoback, M. D., 1985, Journal of Geophysical Research, 90: 8691–8706.

21. Proposed waste packages walls [*5*] are 2 cm Cr-Ni-Mo alloy over 5 cm stainless steel and are designed to protect against low-temperature aqueous corrosion. Although these alloys have not been evaluated directly for response to basaltic magmatic conditions, analog alloys have significant changes in microstructure and reductions in mechanical strength when exposed to only 600–800 °C for tens to hundreds of hours (e.g., Rebak, R.B., Summers, T.S.E., and Carranza, R.M., 1999, Boston Meeting, Paper QQ 14.4, Boston, MA: Materials Research Society). Inner stainless steel walls also have a roughly 30 percent greater thermal expansivity than outer alloy walls (e.g., American Society of Mechanical Engineers, 1998, Boiler and Pressure Vessel Code, Section II, Part D – Properties), leading to potentially significant hoop-stress on waste package walls. Following [*11*], we also assume that waste canisters wholly engulfed by basaltic magma will be breached and expose high-level waste to the flowing magma.

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Figures

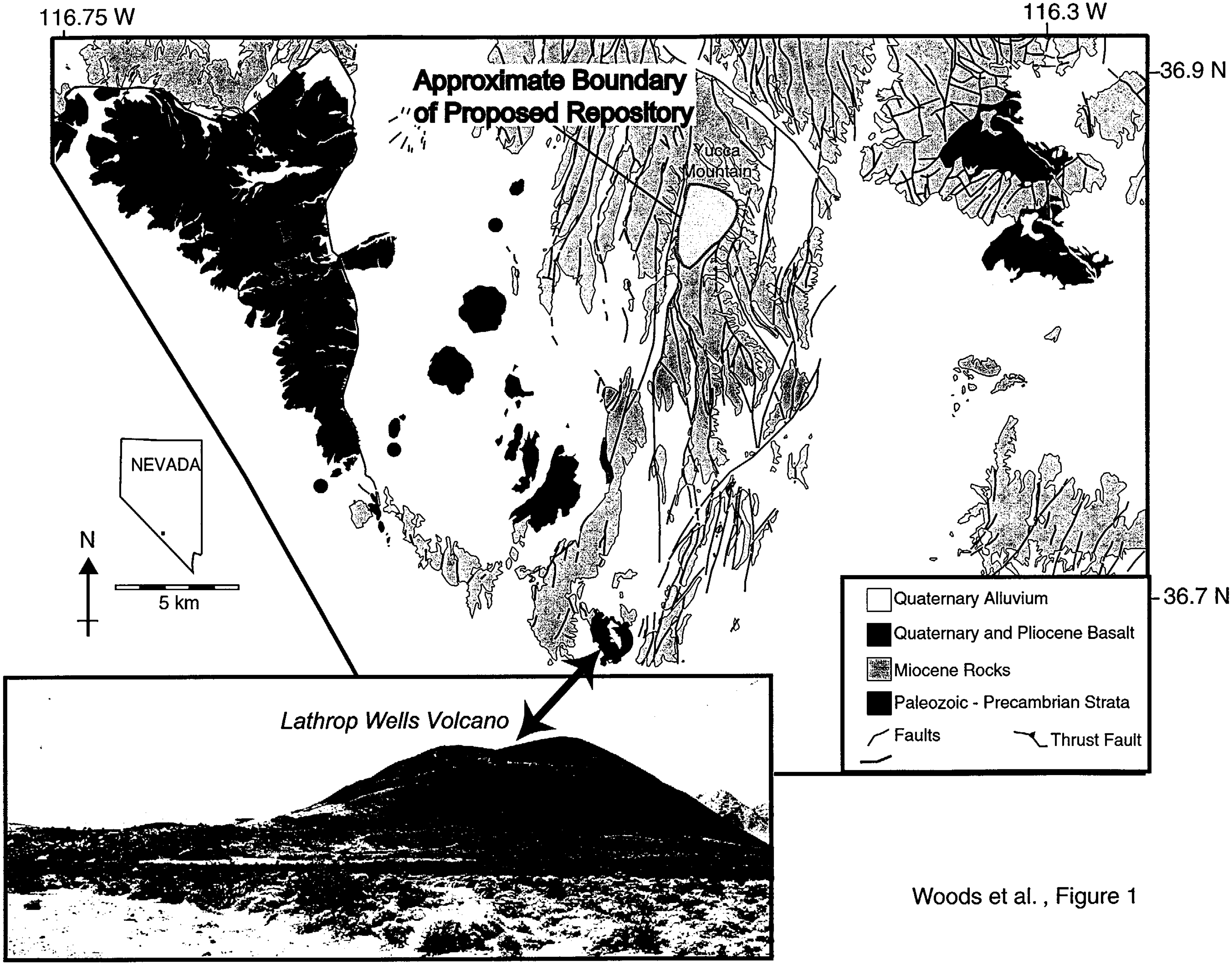
Figure 1. Map of area including proposed site of repository and proximity of Pliocene and Quaternary basaltic volcanoes (red, shown as red circles where inferred from magnetic anomalies [*3*]. Lathrop Wells volcano (photo) is the youngest cinder cone in the region (~80 ka).

Figure 2. Schematic of (a) the proposed repository, (b) a repository drift with waste canisters, and (c) the model geometry used to estimate pressure and velocity within drifts during initial stages of magma intrusion. (a) and (b) modified from U.S. Department of Energy [*11*]. Plans call for individual drifts (b) to be parallel and spaced 80 m apart.

Figure 3. Calculations of (a) pressure and (b) velocity as a function of position along the drift and dike, for basalt with 2 wt percent water, during the initial few seconds after rupture of the dike into the drift. (i) The shock wave may be seen propagating towards the end of the drift. In (ii–v), the shock is reflected at the drift end and is amplified by a factor of order 20. When this shock moves backwards into the oncoming magma, the mixture is compressed. This dense high pressure magma may then drive a fracture from the drift to the surface if there is a point of weakness or low stress in the rock surrounding the drift.

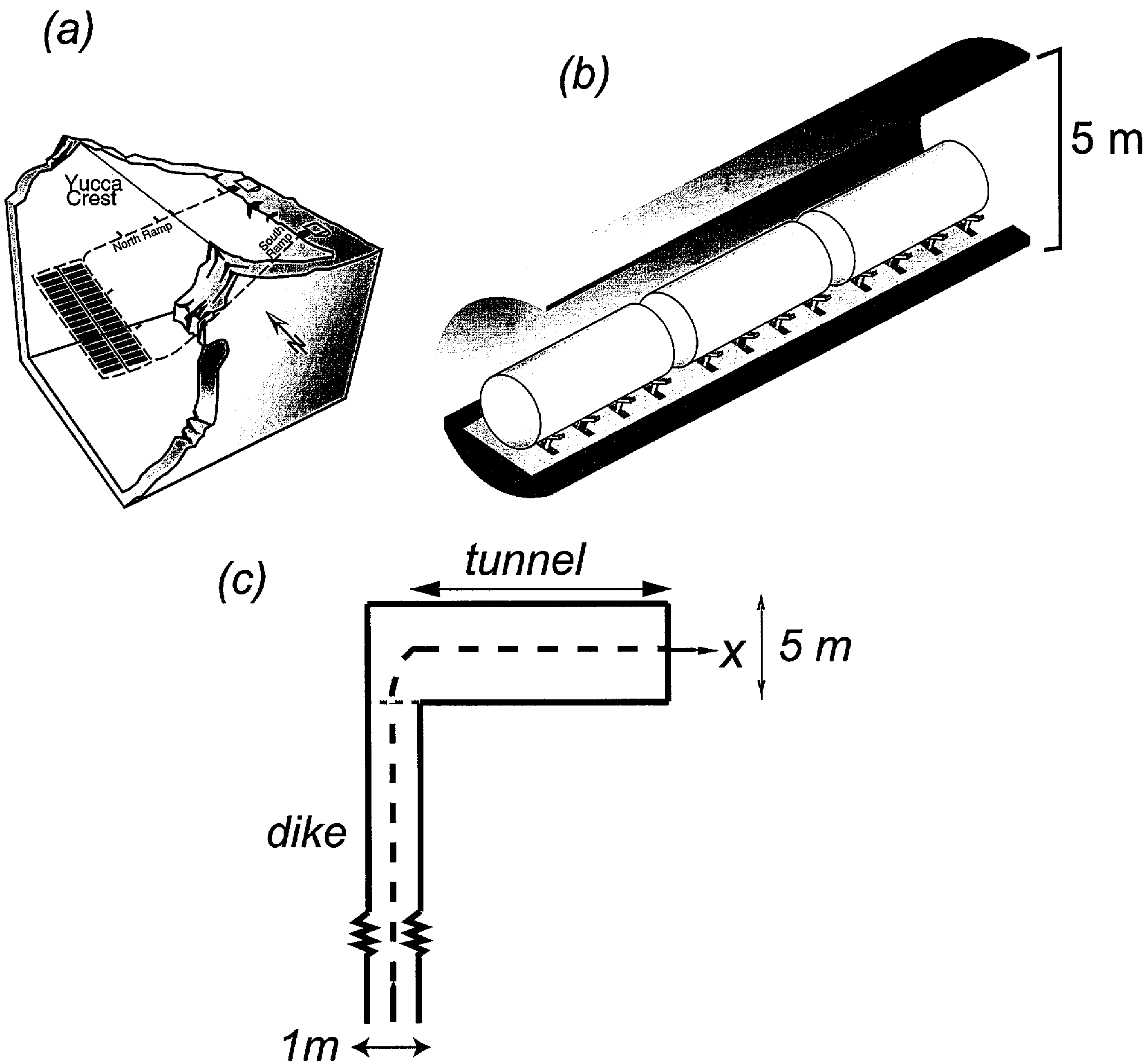
Figure 4. Schematic of the steady flow geometry that may enable a steady basaltic eruption to develop: (a) with flow along the original dike; (b) with magma being diverted along the drift before surfacing along a new fissure; and (c) with magma being diverted along the drift and into the main access drift from where it vents to the atmosphere.

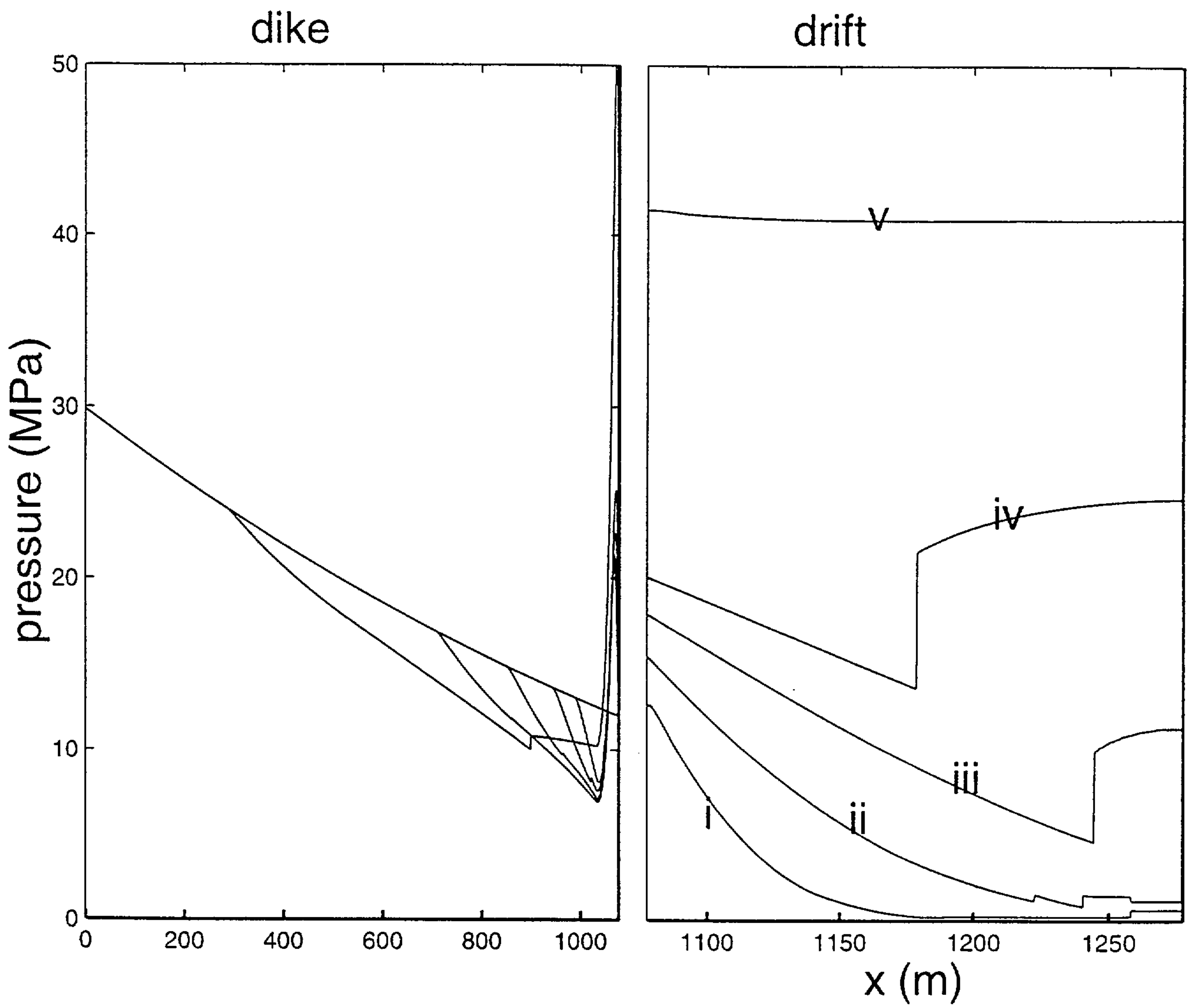
Figure 5. Calculation of (a) pressure and (b) velocity as a function of position along the flow path from the magma reservoir, along the dike, drift and conduit to the surface. In cases 2 and 3, the drift is assumed to be 500 m long, and located 300 m below the surface. In case 2, the magma moves along the drift and then upwards through a fissure to the surface. In case 3, the magma flows along the 4-km-long access drift from the drift to the surface.



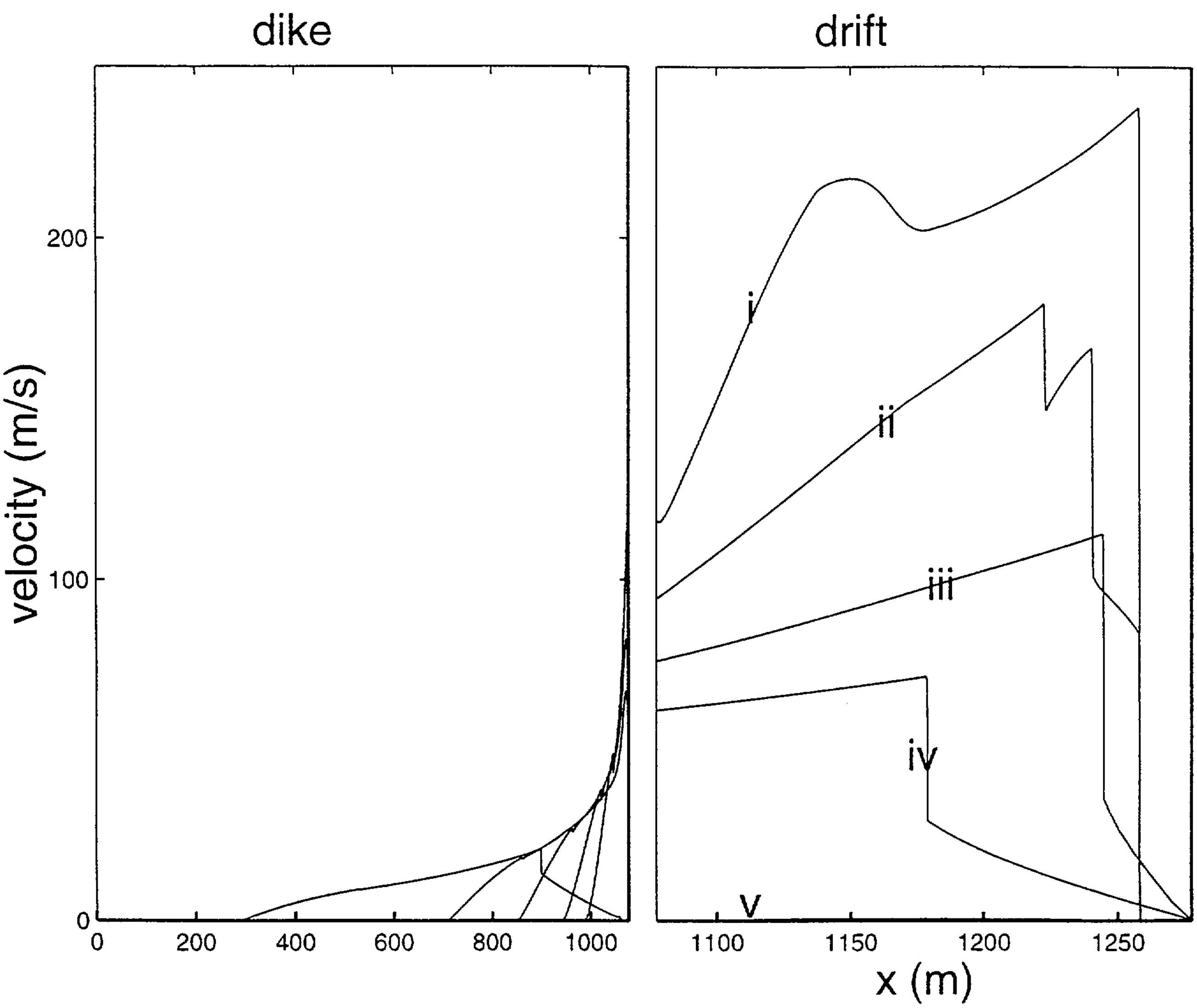
Woods et al. , Figure 1

Woods et al., Figure 2

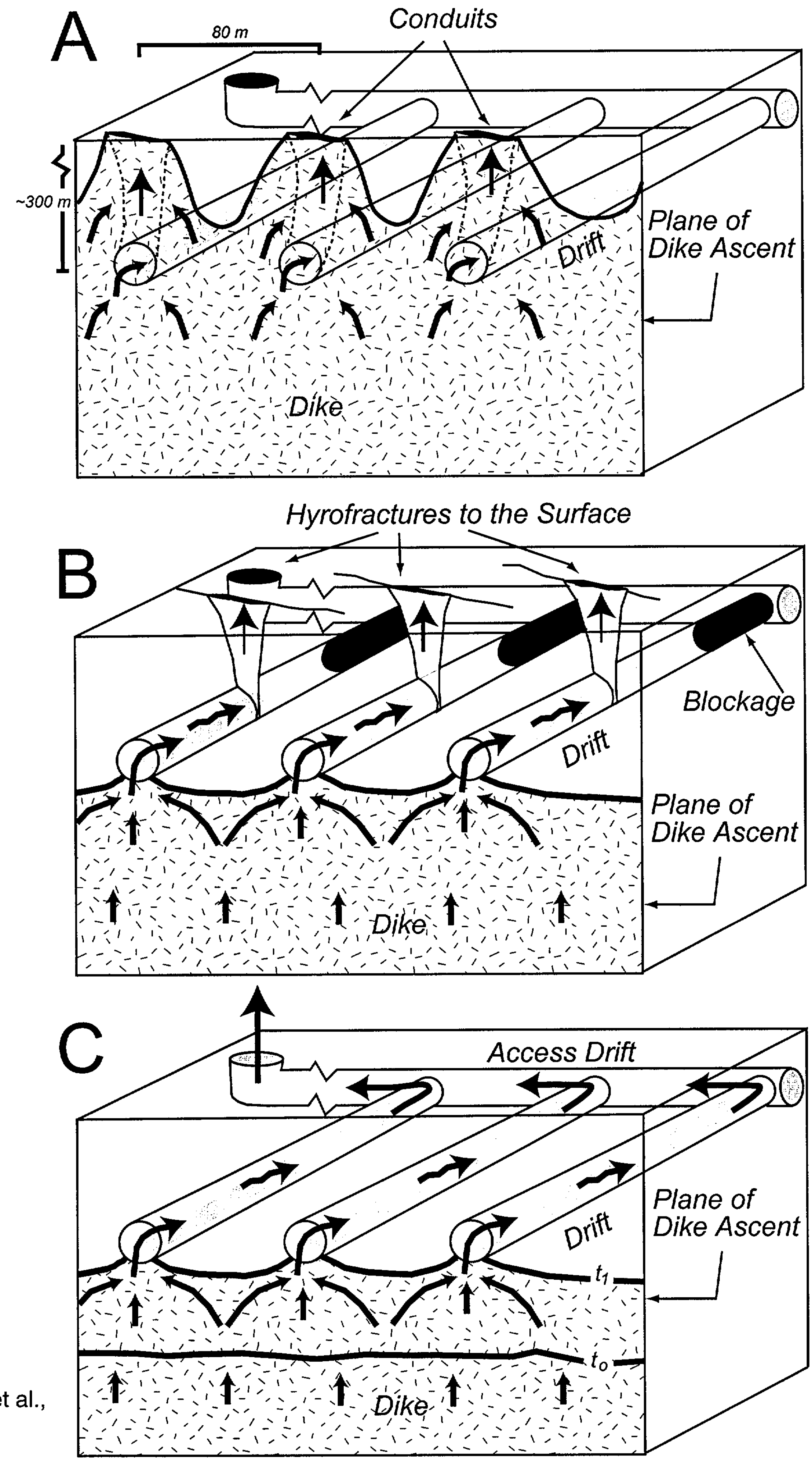




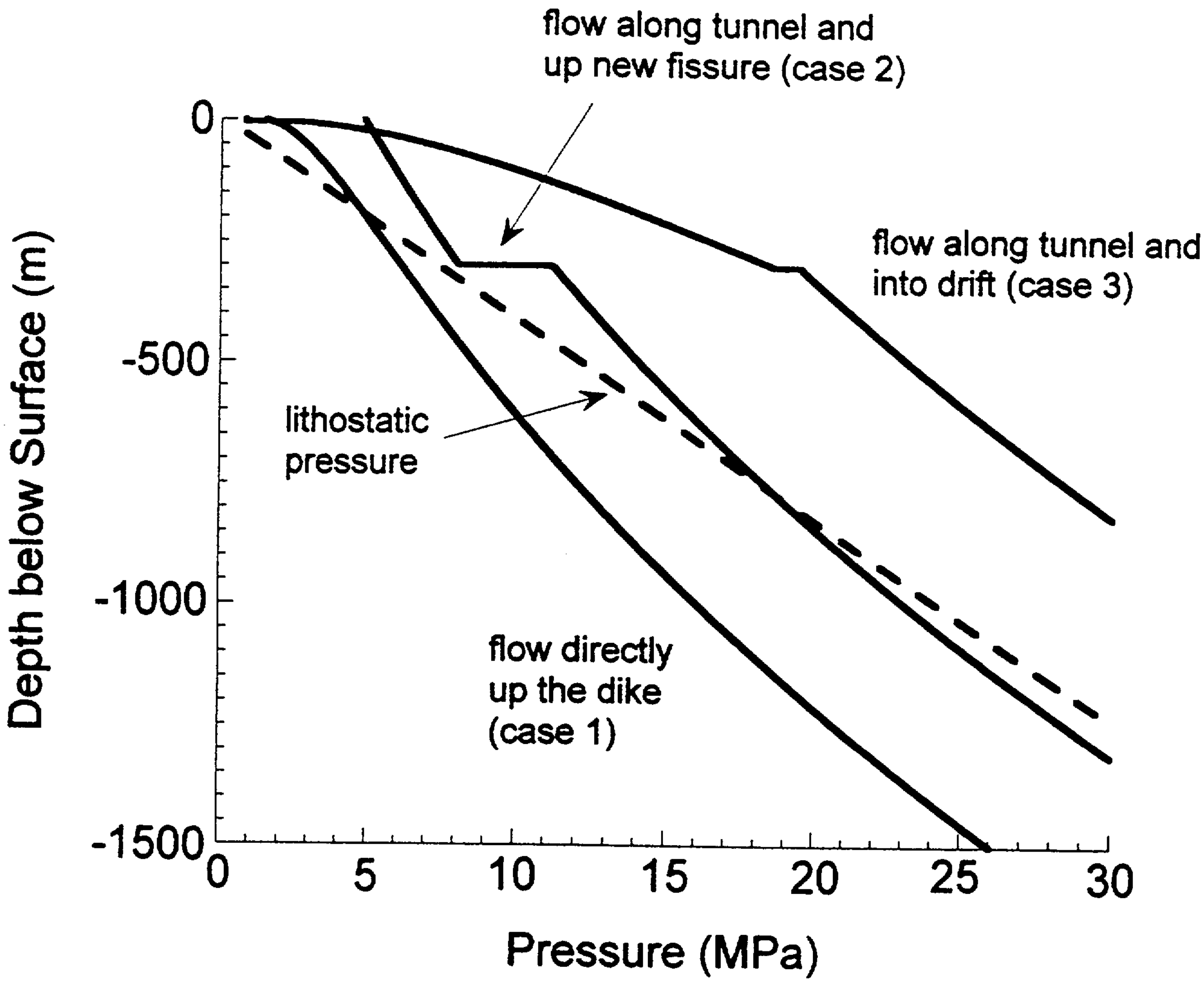
Woods et al., Figure 3a



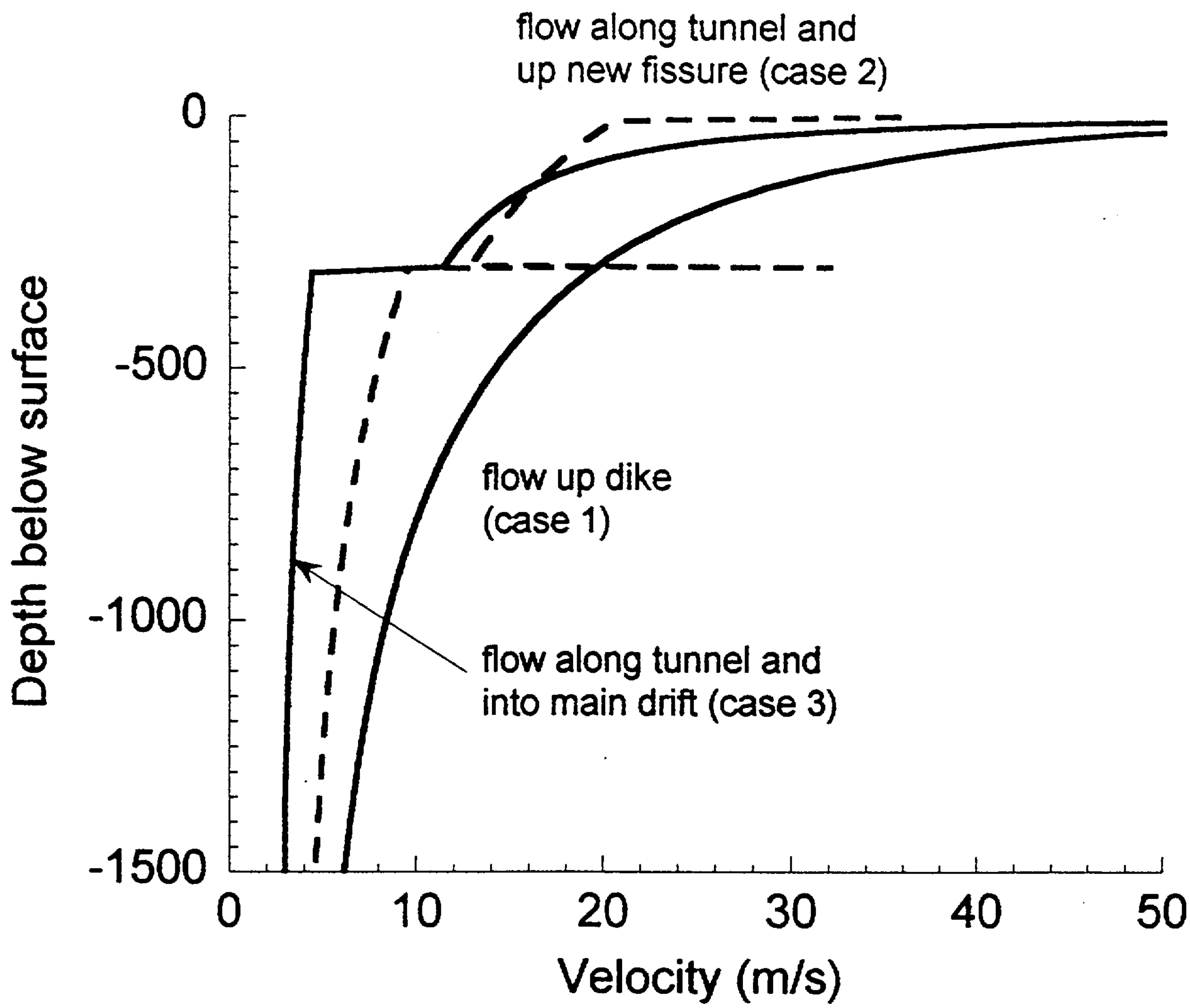
Woods et al., Figure 3b



Woods et al.,
Figure 4



Woods et al., Figure 5a



Woods et al., Figure 5b