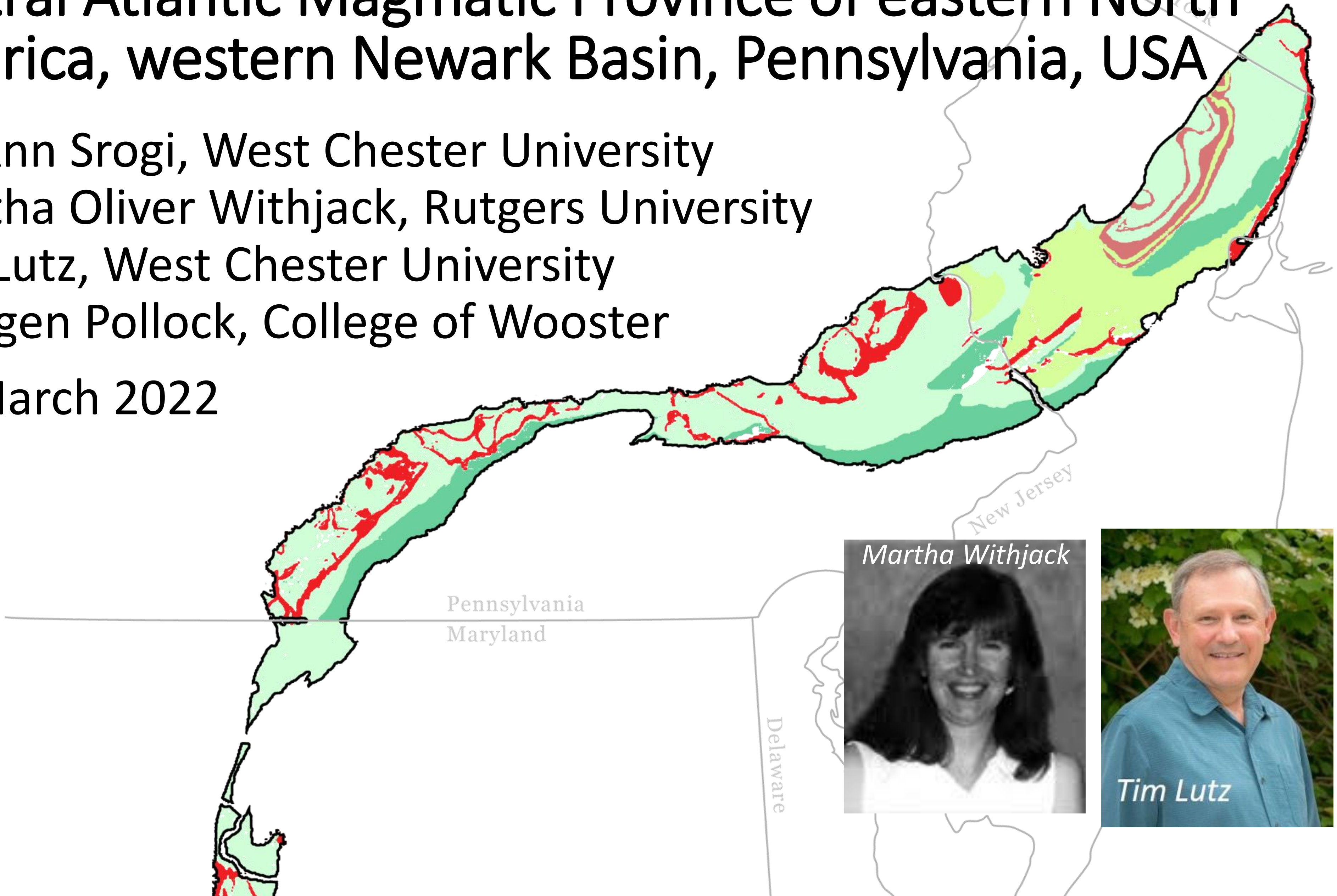
Magma reservoir depths and magma transport in the Central Atlantic Magmatic Province of eastern North America, western Newark Basin, Pennsylvania, USA

LeeAnn Srogi, West Chester University
Martha Oliver Withjack, Rutgers University
Tim Lutz, West Chester University
Meagen Pollock, College of Wooster

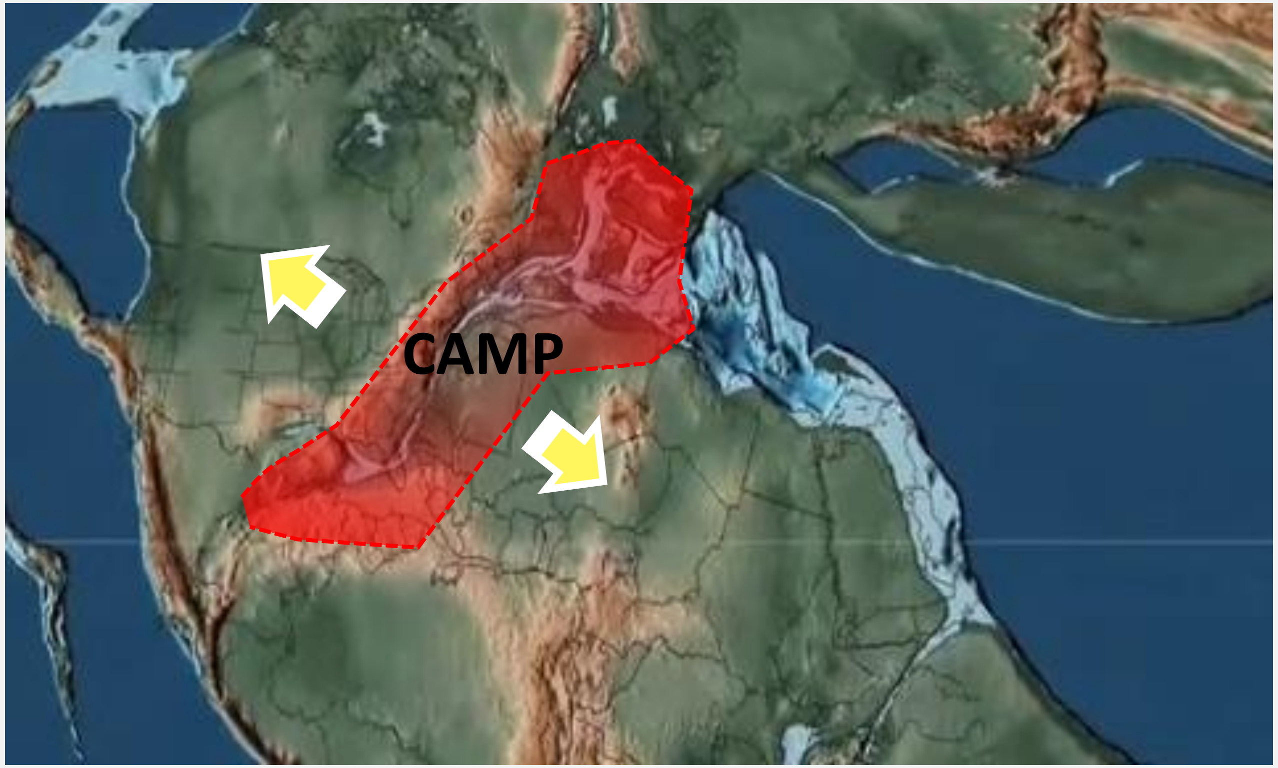
22 March 2022



Central Atlantic Magmatic Province (CAMP)

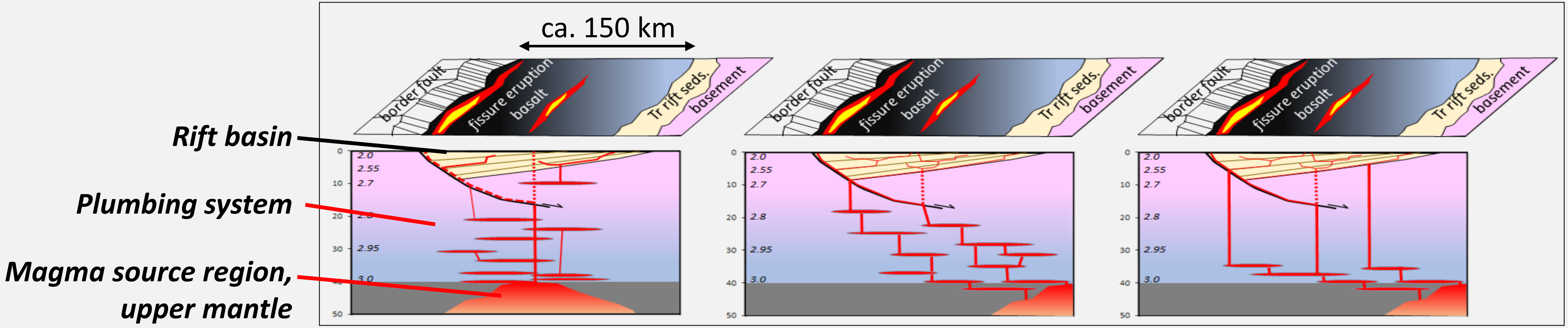
Large Igneous Province (LIP)

- latest Triassic/earliest Jurassic (~201 Ma)
- flood basalt eruption, possibly largest by area in Earth history
- massive event in a short time, ~ 600 ky (600,000 years), Blackburn et al., 2013
- 1st phase is focus of this study, lasted ~ 10-15 ky in Newark basin, (Olsen et al., Field Conference of Pennsylvania Geologists Guidebook, 2018)



Base image from C. Scotese

Central Atlantic Magmatic Province (CAMP)
large flood basalt eruption in short time



Plumbing system: network of intrusions (dikes, sills, etc.) that carry magma up through the crust from source to volcano; 3 hypothetical examples shown above

Two questions addressed in this talk: 1) What was the CAMP plumbing system like, in rift basins and between source and basin?

2) How did magma transport in the plumbing system influence magma flux and eruption?

Outline of presentation

- CAMP plumbing system in the rift basin – a quick summary of the previous talk by Martha Withjack
- Magma transport and flow within the rift-basin plumbing system
- CAMP plumbing system in the crust between the magma source region (upper mantle) and the rift basin (~ 8 to 40 km)
- Magma transport and flow in the trans-crustal plumbing system

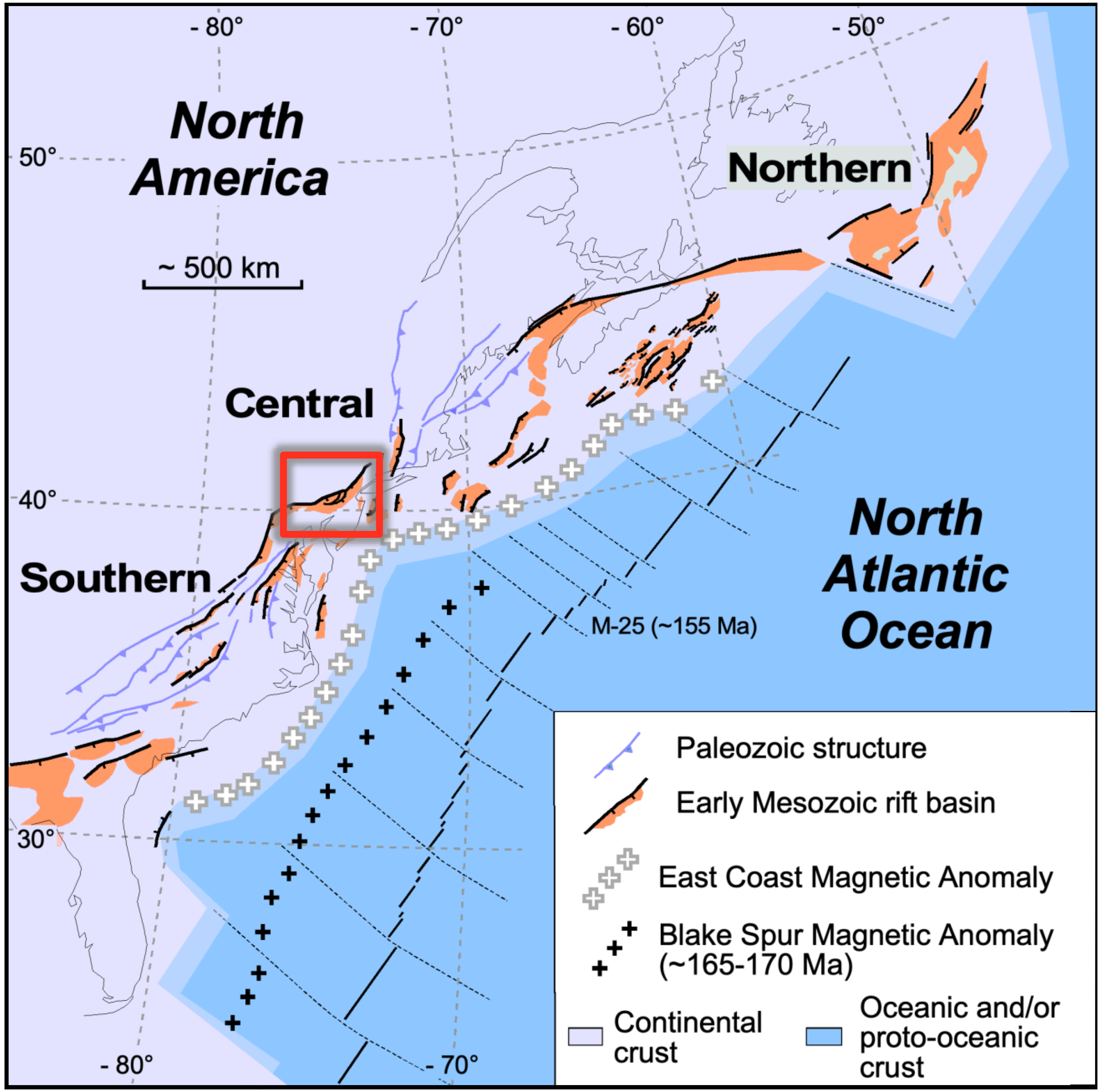
Study Area: Newark rift basin and Narrow Neck

Within central segment of Eastern North American (ENA) rift system

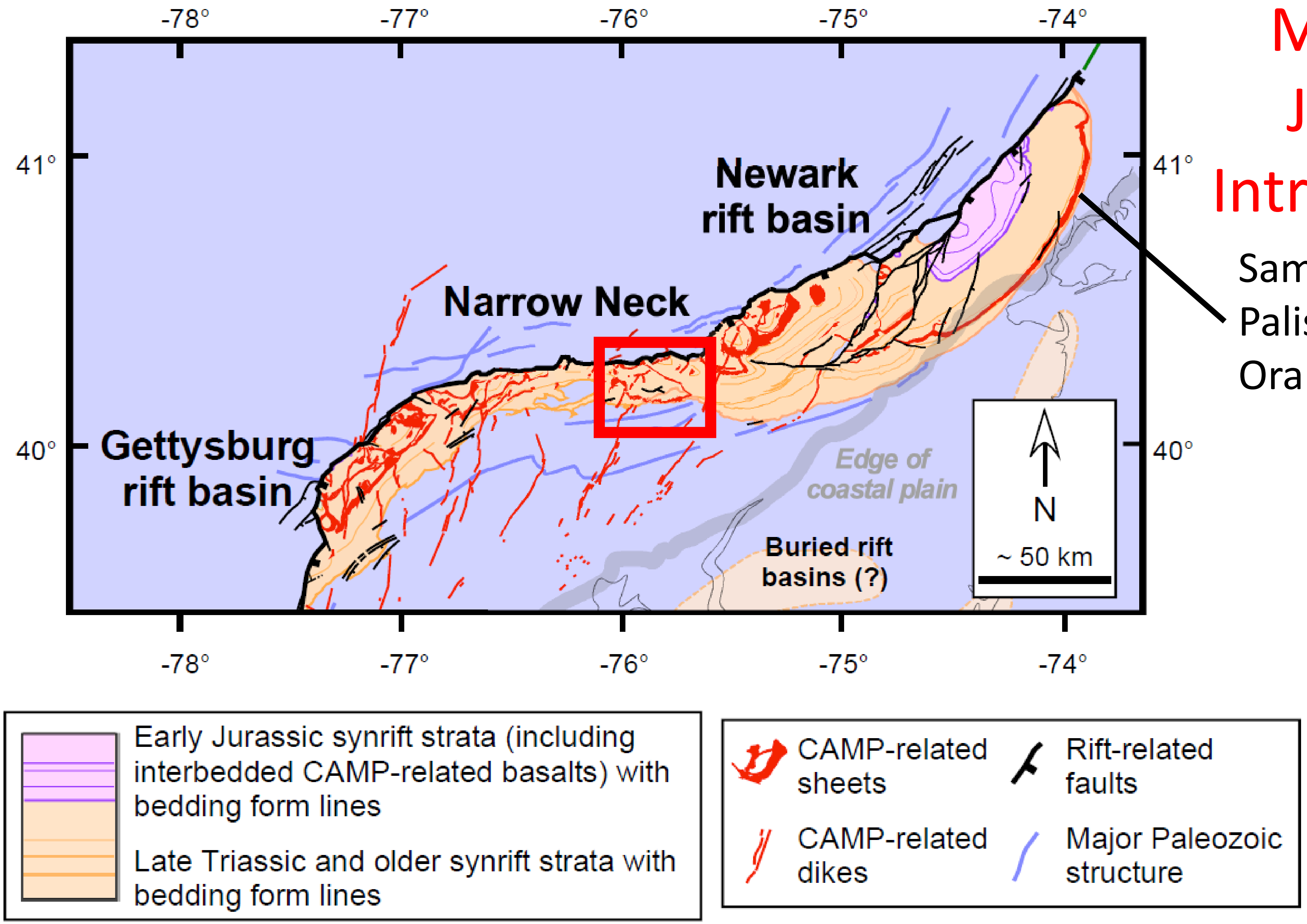
Rifting began by Late Triassic and continued into Early Jurassic

CAMP-related magmatic activity during rifting (~201 Ma)

Located hundreds of kilometers from eventual site of breakup



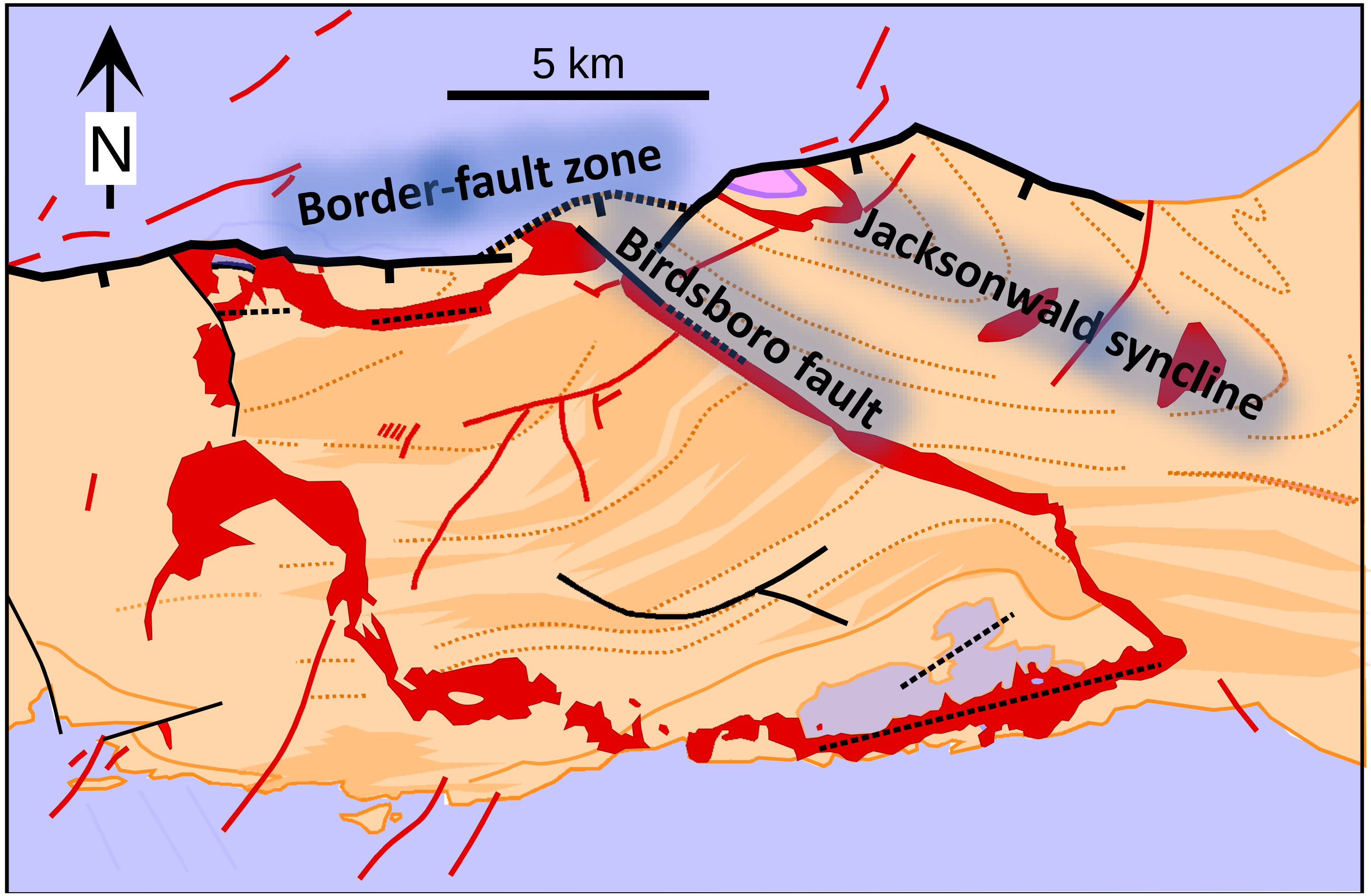
Morgantown-Jacksonwald Intrusive Complex

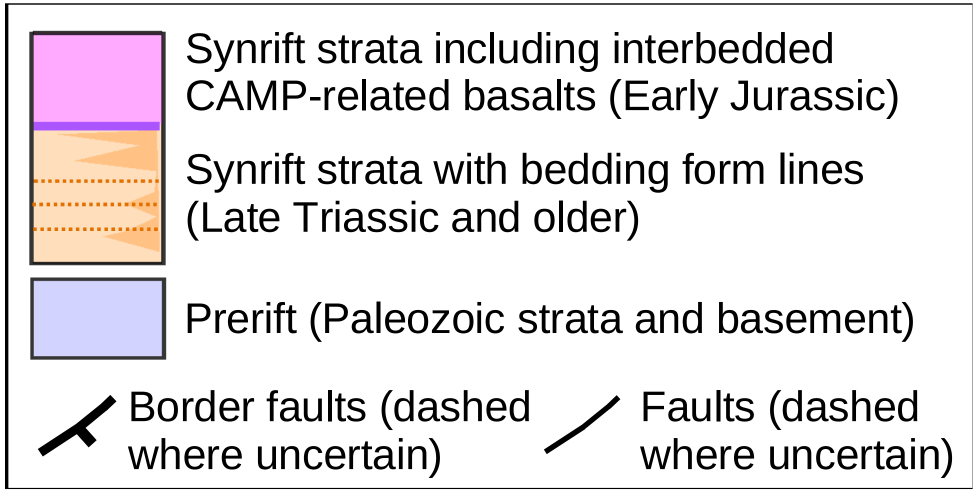


Same magma and age as Palisades sill, NJ-NY, and Orange Mtn basalt, NJ

Image: http://en.wikipedia.org/wiki/Palisades_Sill

Geologic Map of Morgantown-Jacksonwald Intrusive Complex





Post-magmatic movement along faults

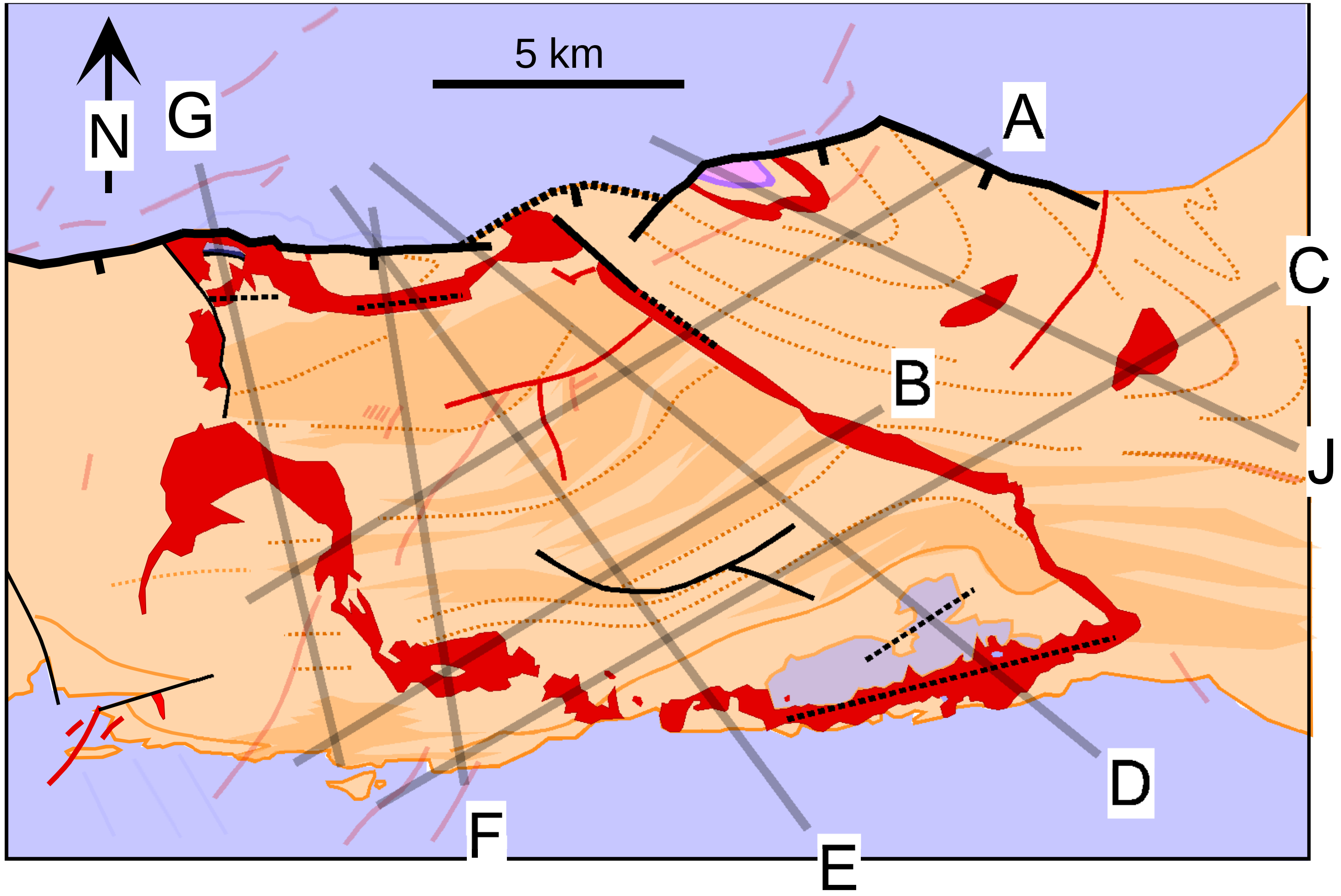
All rocks in the basin (including all igneous intrusions and lava flow) were tilted NW towards the Border Fault

Rocks in Jacksonwald syncline were also folded

Correct for tilting, folding to reconstruct original shape of intrusion

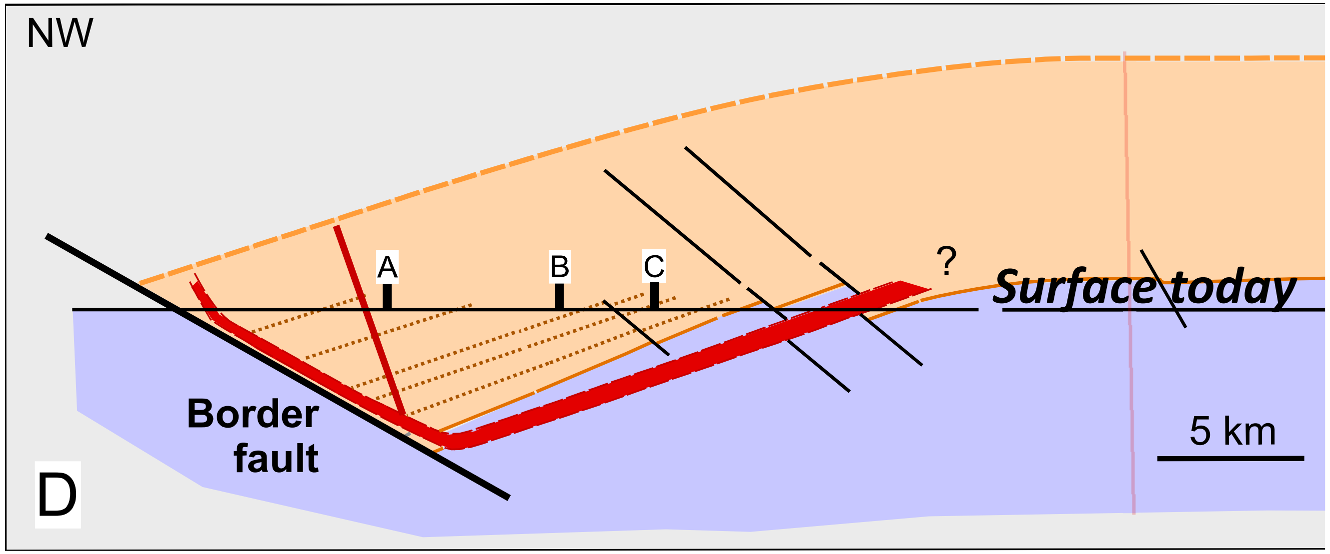
Geologic Map of Morgantown-Jacksonwald Intrusive Complex with Cross Section Locations

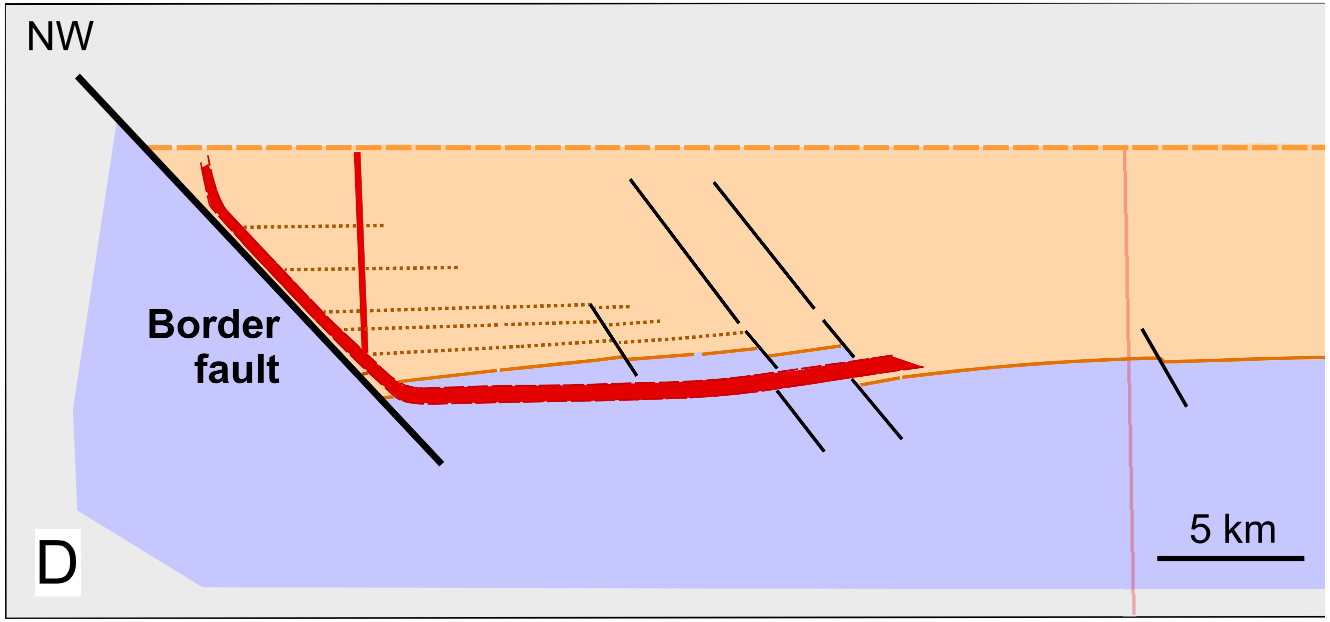
Structural cross-sections by Martha Withjack (previous talk)



Cross-section D (next slide)

Geologic Cross Section D
Morgantown Intrusive Complex





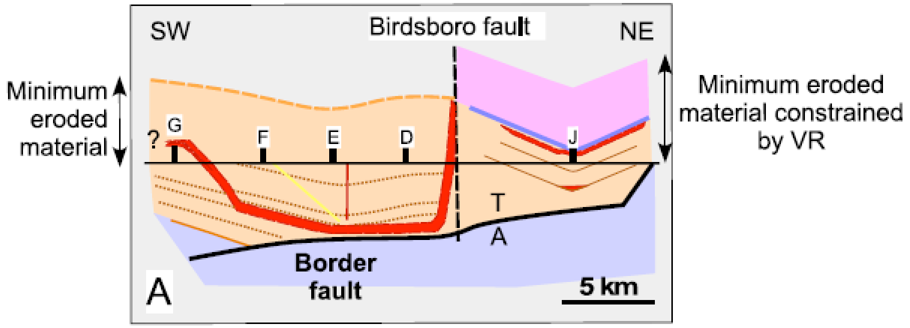
Cross-section today with rock removed by erosion added back on top

Cross-section at time of emplacement – corrected for tilt, folding, eroded material

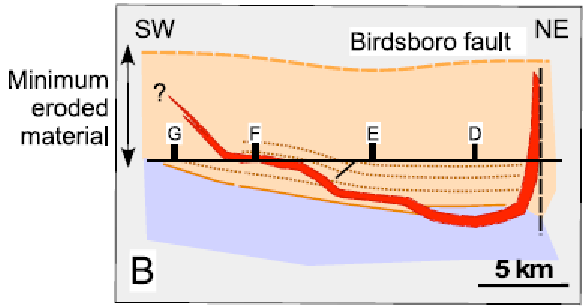
asymmetric intrusion

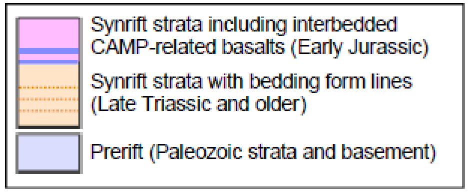
- ***sill at base of rift basin***
- ***steeply-dipping sheet (dike) along border fault***

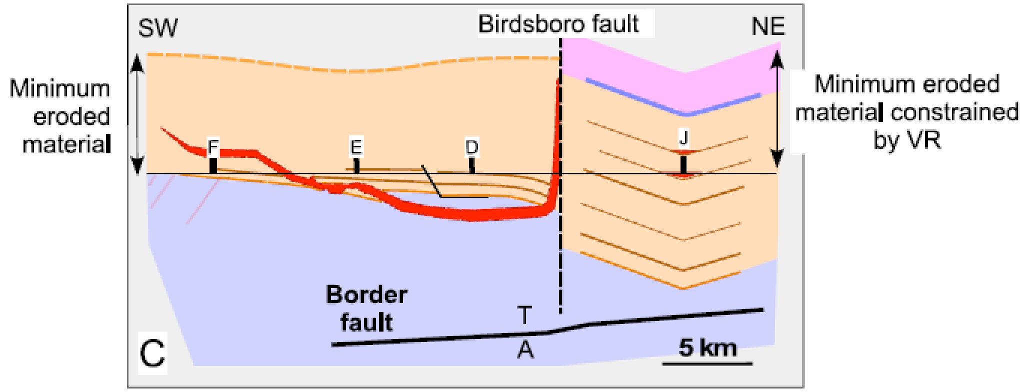
Cross Sections A, B, C at Time of Emplacement



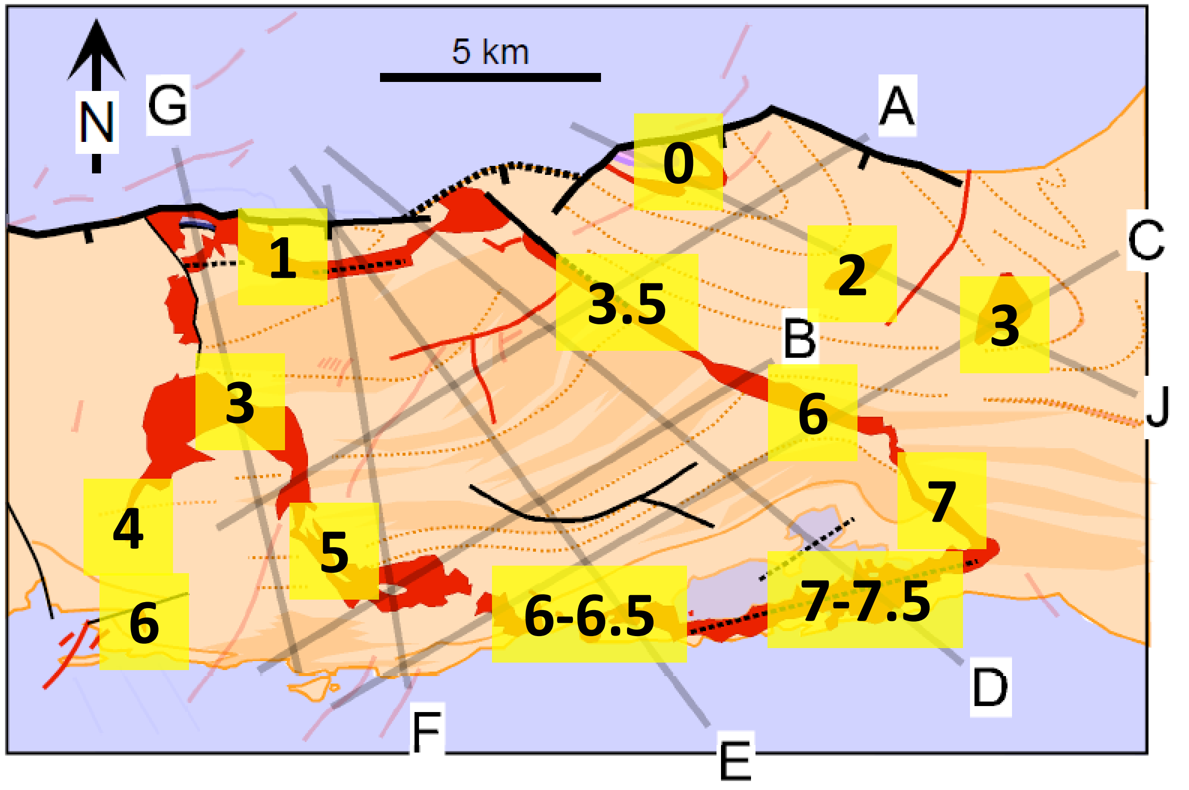
Igneous sheet climbs up-section in northeast along Birdsboro fault (dike) and towards the west in series of steps



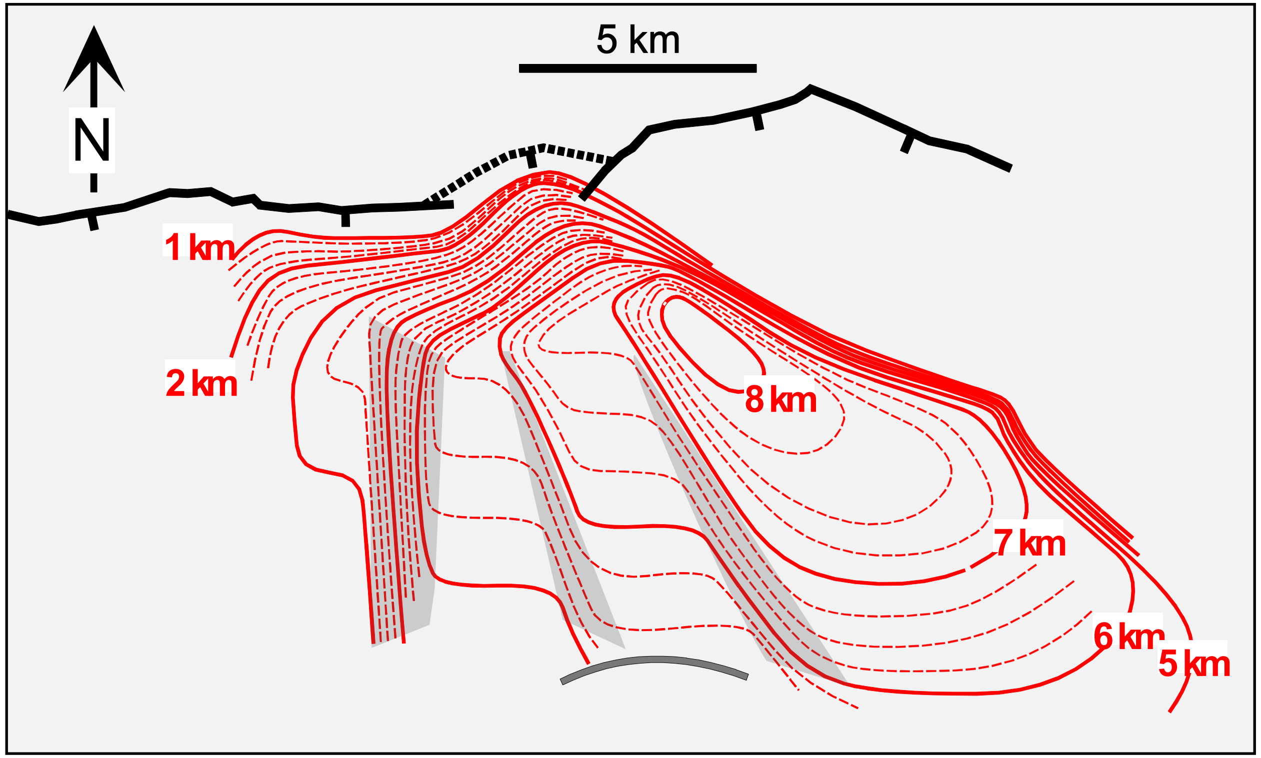




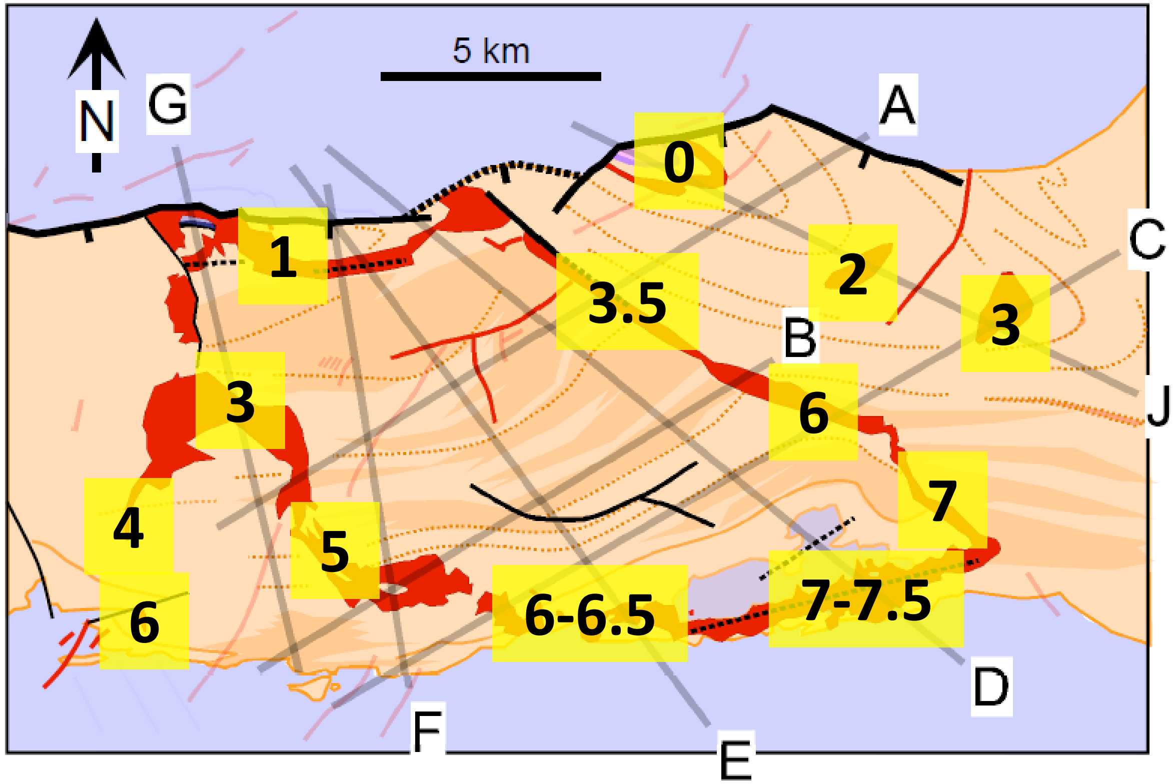
Martha Withjack estimated depths of emplacement (yellow numbers, in km)



Martha Withjack's Structure Contour Map: Top Surface of Morgantown Intrusive Complex at Time of Emplacement

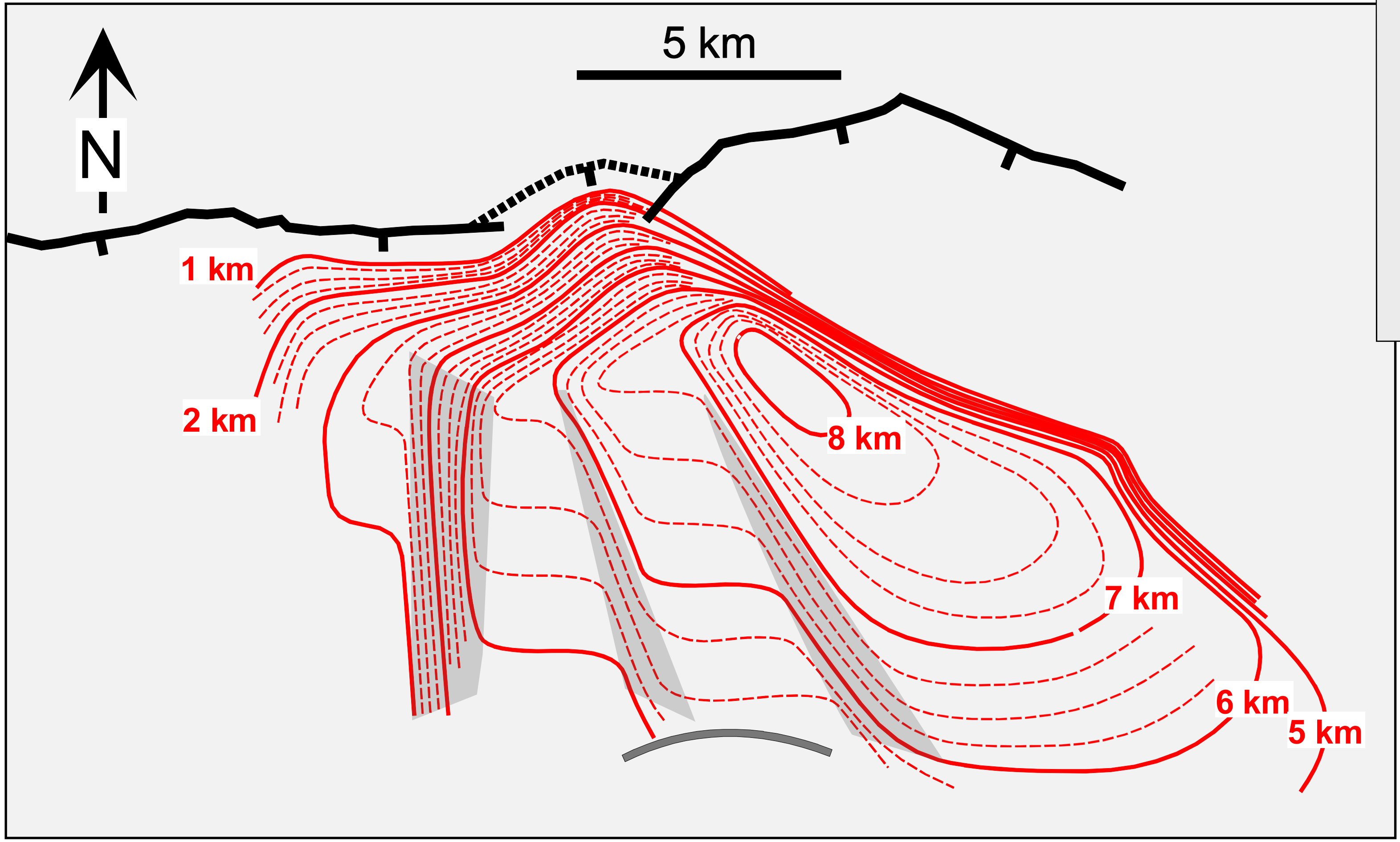


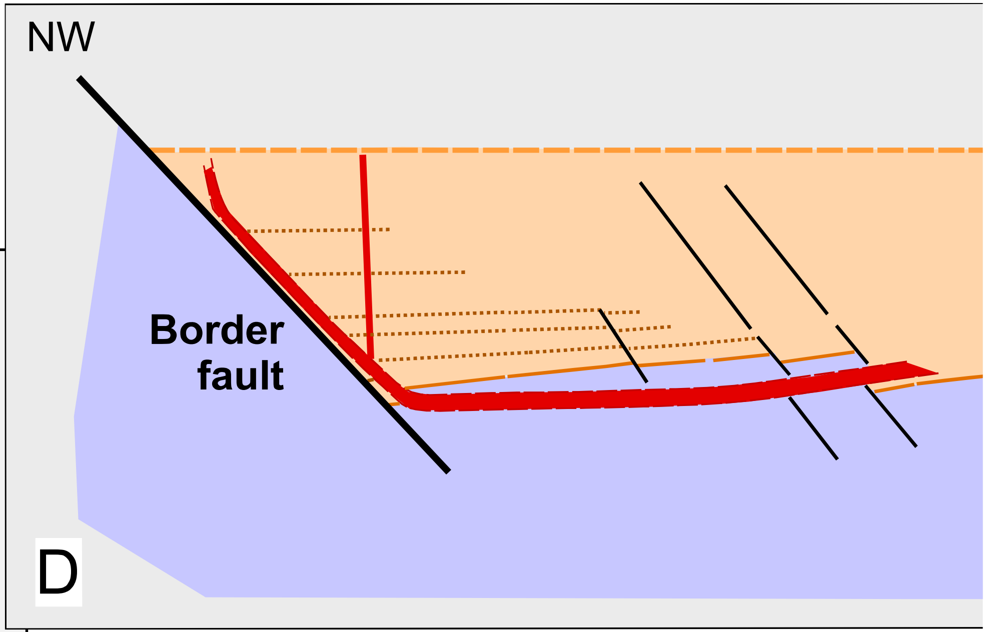
emplacement depths (km)



"… a map view of the tilted, asymmetrical, deeply-eroded early Mesozoic basins of the Eastern United States offers a natural tangential cross-section." (Froelich and Gottfried, 1985, p. 84)

Martha Withjack's Structure Contour Map: Top Surface of Morgantown Intrusive Complex at Time of Emplacement





Complex shape

sub-horizontal sill segments

steeply-dipping segments
(ramps, dikes)

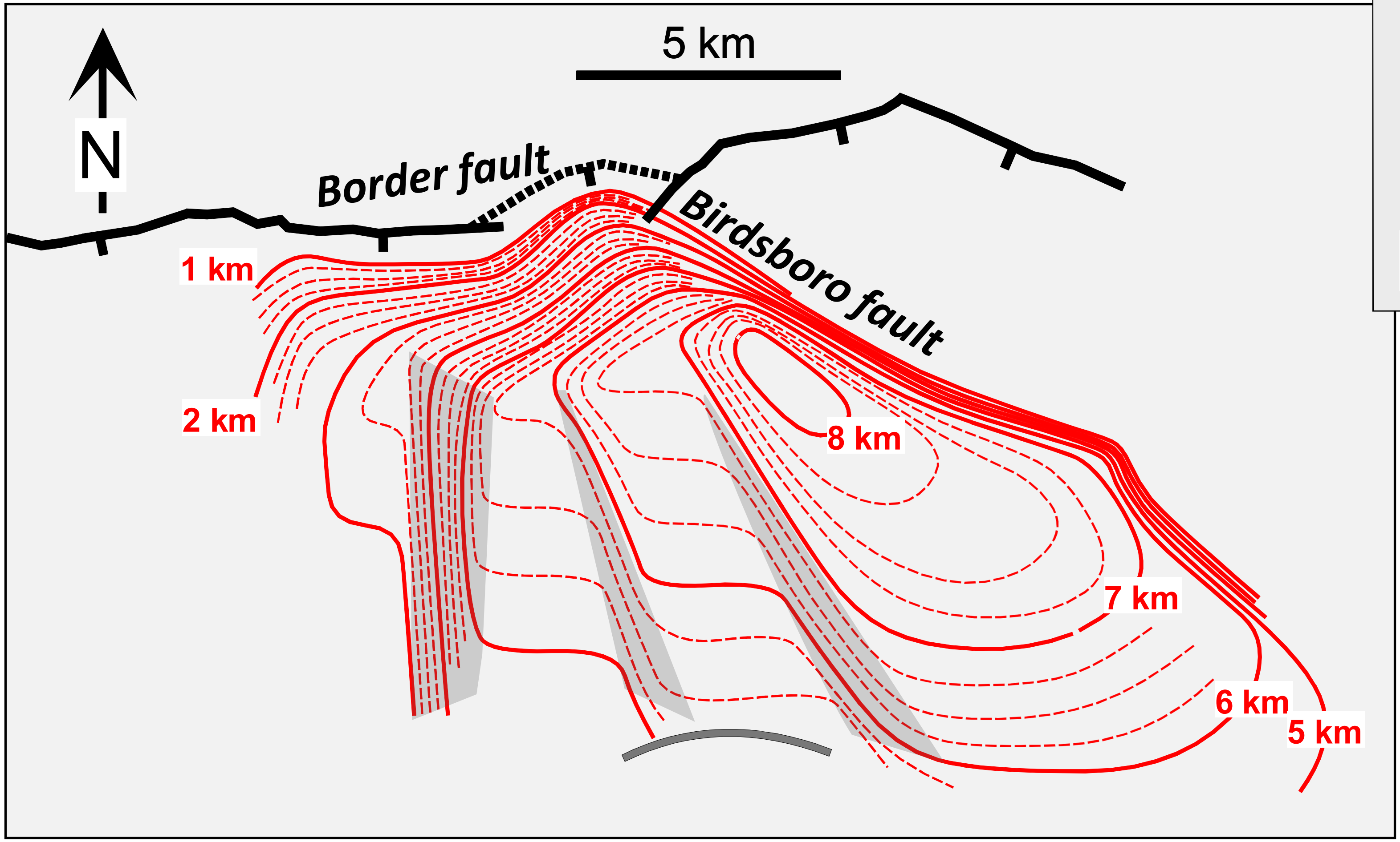
> 8 km below surface at deepest point, at time of emplacement

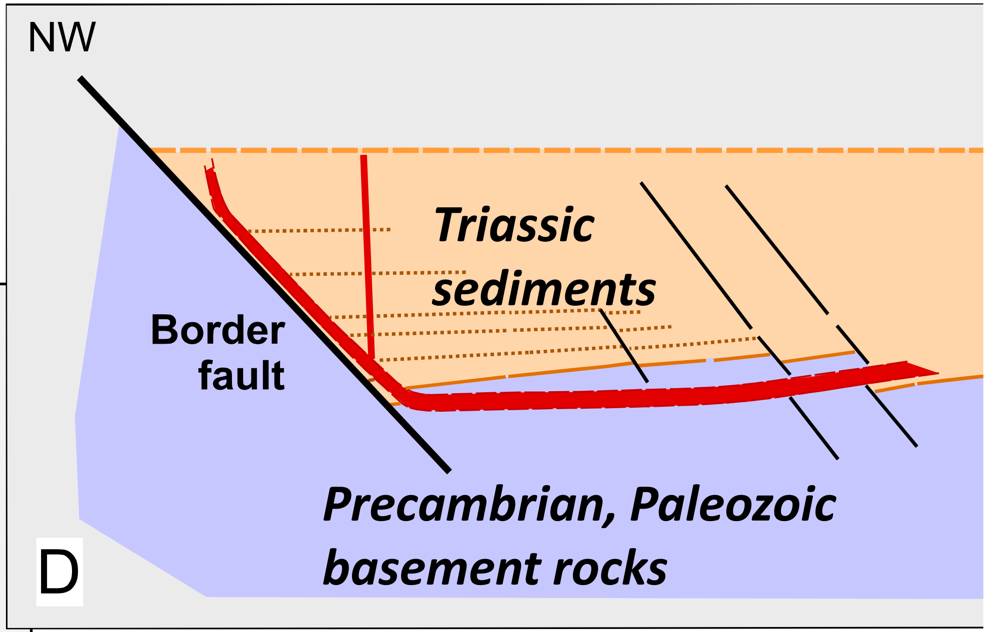
Can we reconstruct magma flow from shape?

Outline of presentation

- CAMP plumbing system in the rift basin – previous talk by Martha Withjack
- Magma transport and flow within the rift-basin plumbing system
- CAMP plumbing system in the crust between the magma source region (upper mantle) and the rift basin (~ 8 to 40 km)
- Magma transport and flow in the trans-crustal plumbing system

Magma flow followed pre-existing structural zones of weakness

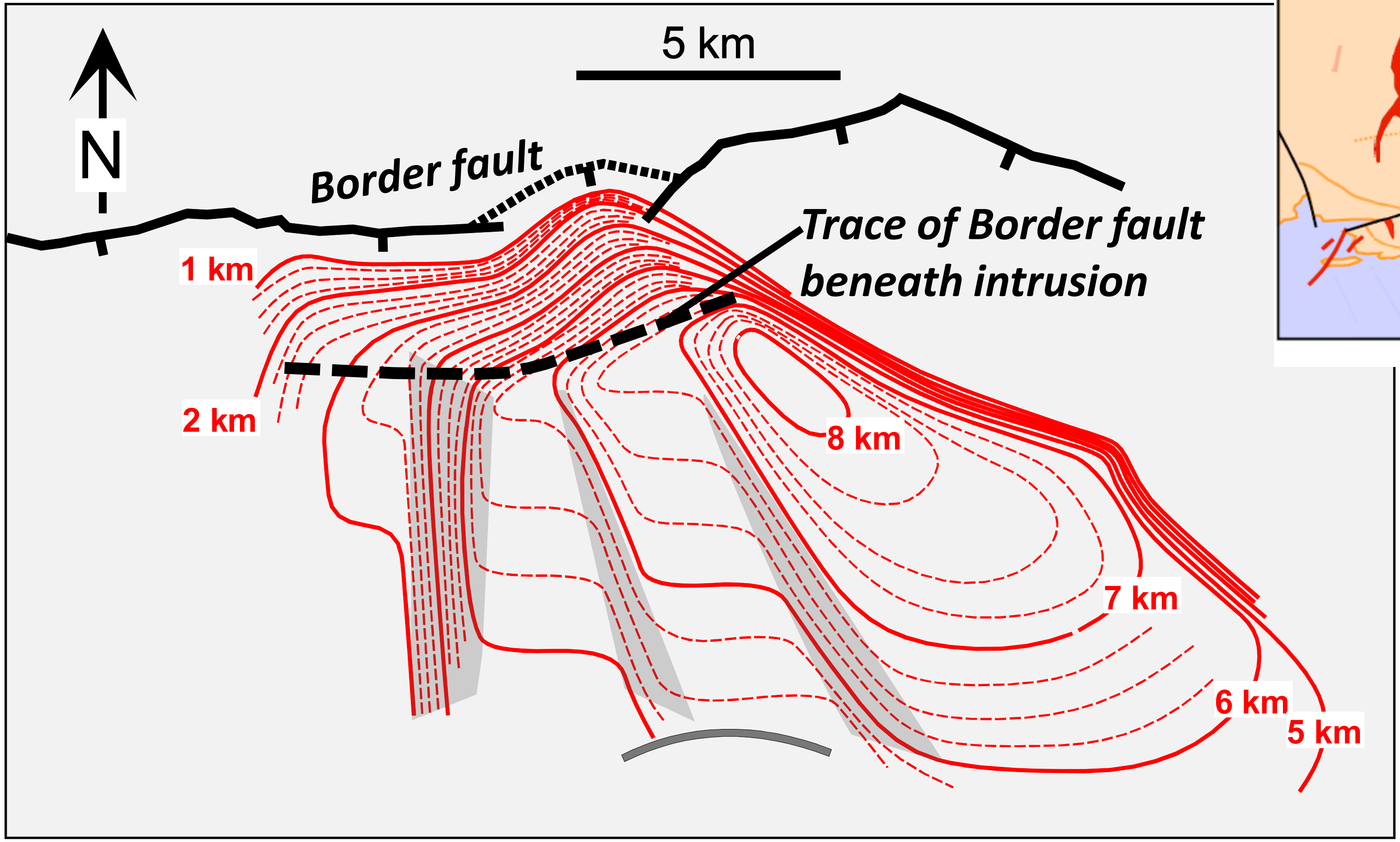


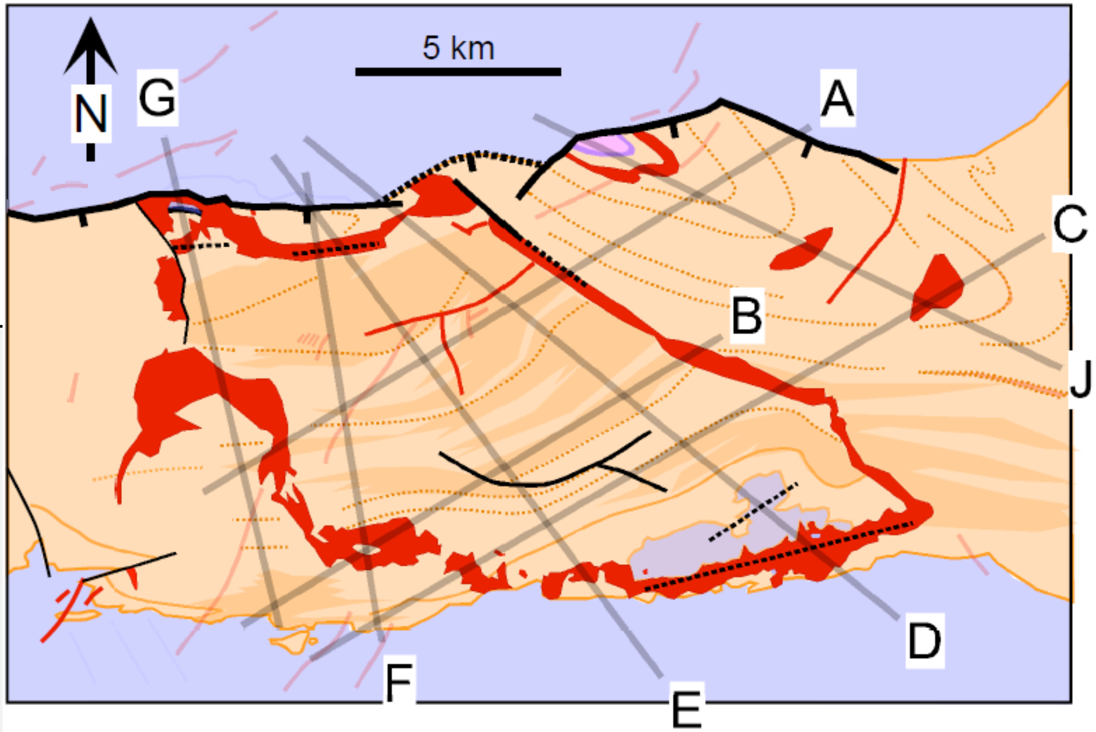


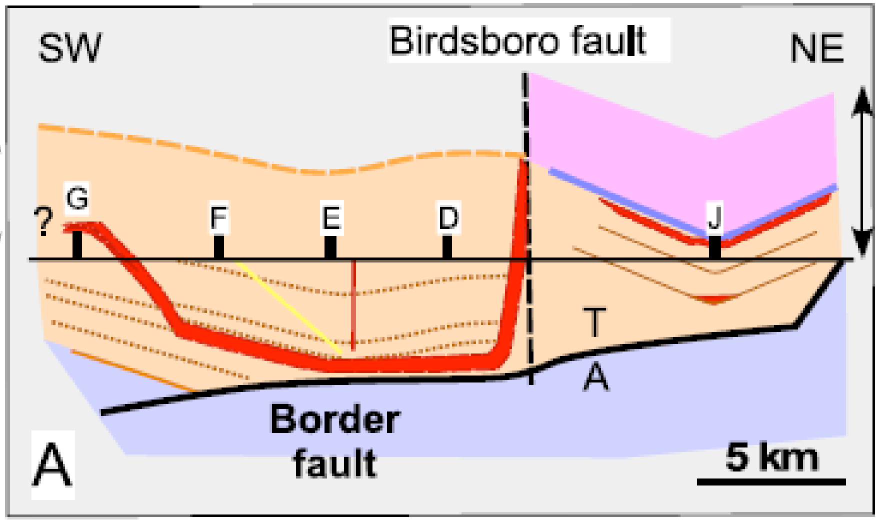
Zones of weakness:

- Base of rift basin (SE): faulted lithologic contact
- Border fault (N side)
- Birdsboro fault (NE side)
- Sedimentary bedding

Magma Flow is Generally UP
Magma Entered Intrusion at Deepest Point
Feeder: likely that Border fault was conduit; could be another dike buried under intrusion

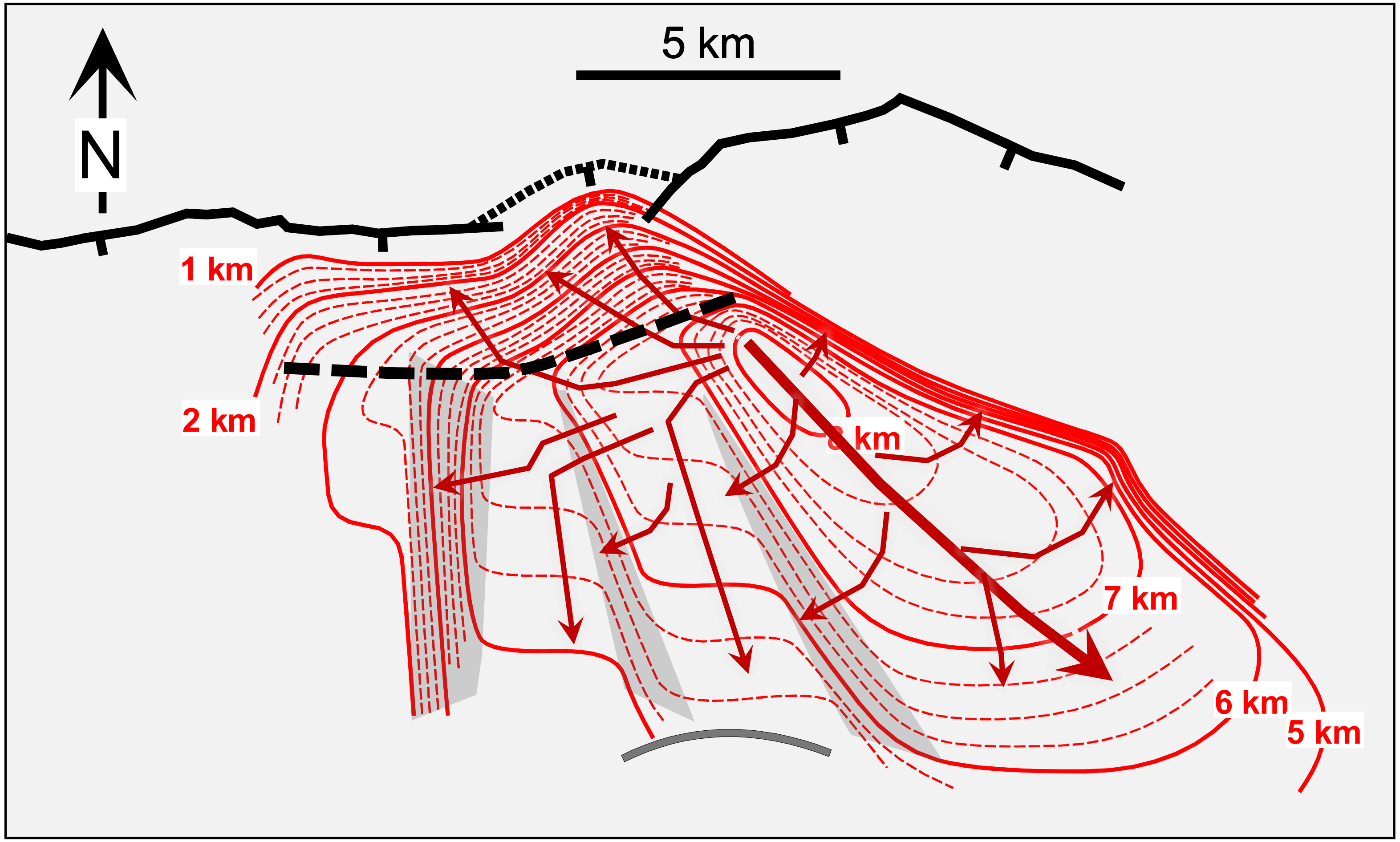




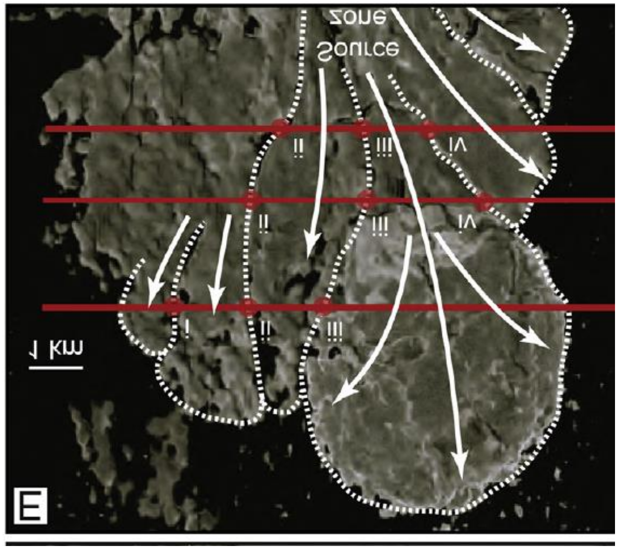


Contour Map of Intrusion Indicates Likely Magma Flow Paths

Proposed flow paths (dark red arrows) are consistent with 3-D seismic studies of sills in buried rift basins



(Magee et al., 2019, Figure 3E of sill in Flett basin, NE Atlantic, rotated 180° and flipped)

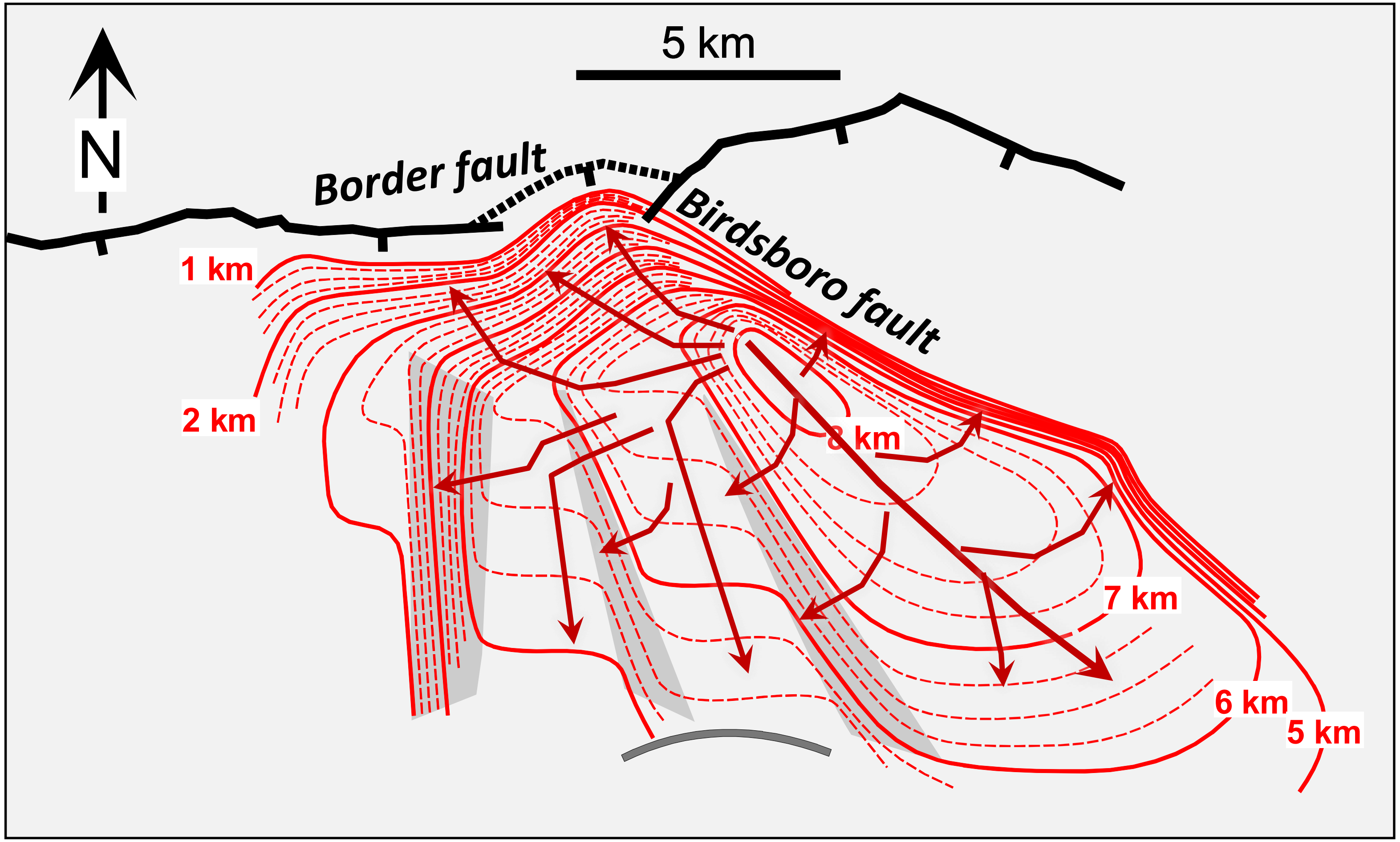


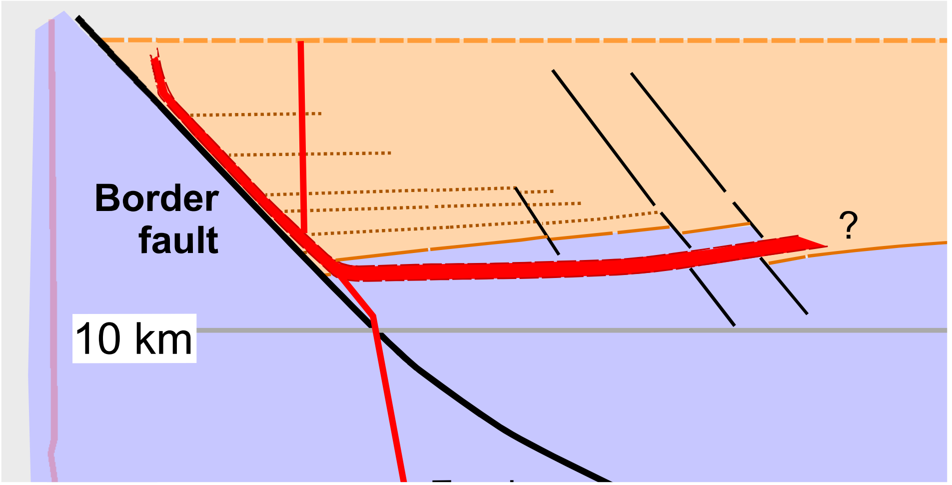
Magma spreads laterally

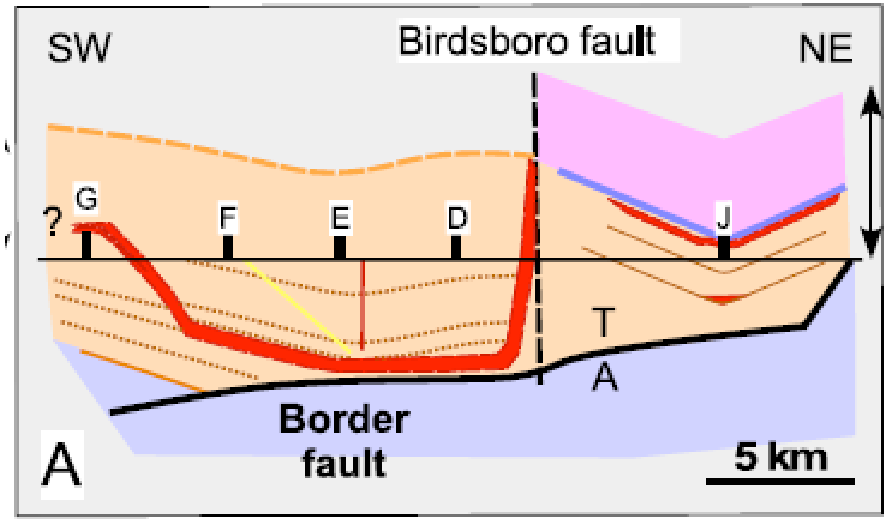
Sill segments get wider in direction of flow

Magma flowed up steeply-dipping segments (Border fault, Birdsboro)

Likely reached surface to feed eruptions of basalt lava



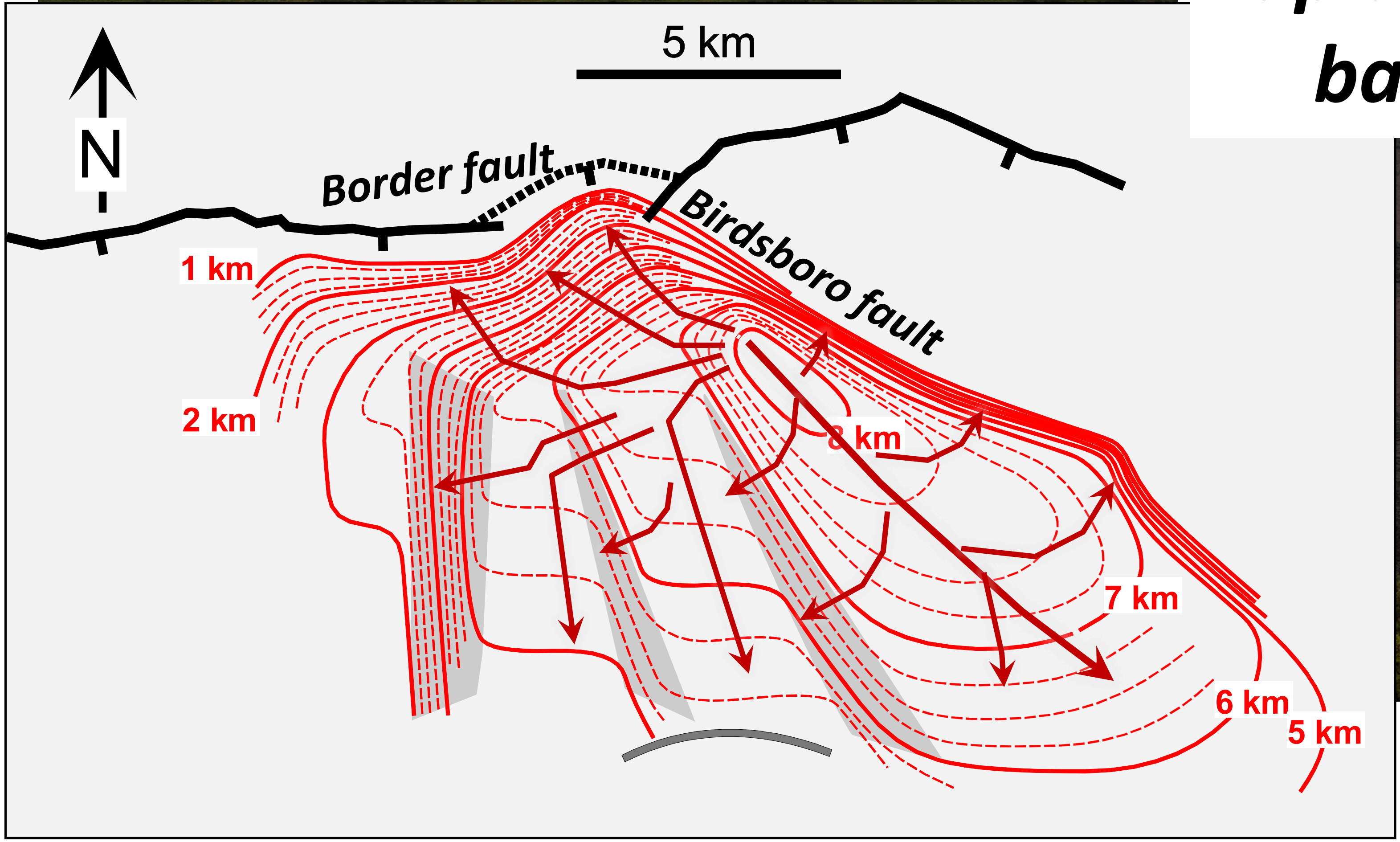




Fissure Eruptions from Dikes along Border Fault and Birdsboro Fault:

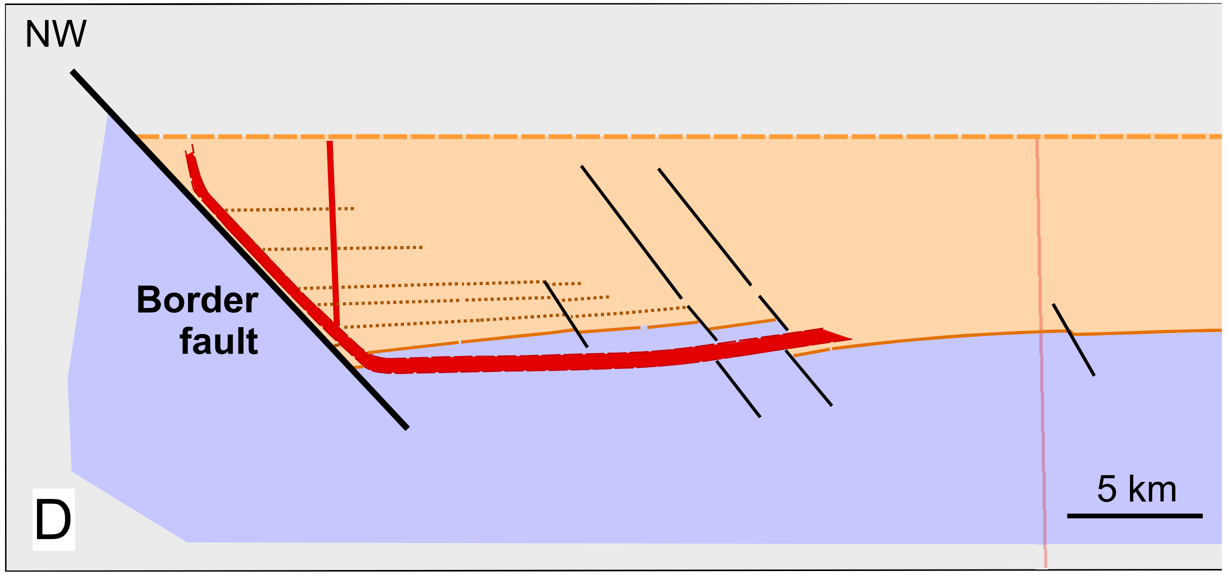
rapid transport through rift basin to eruption sites

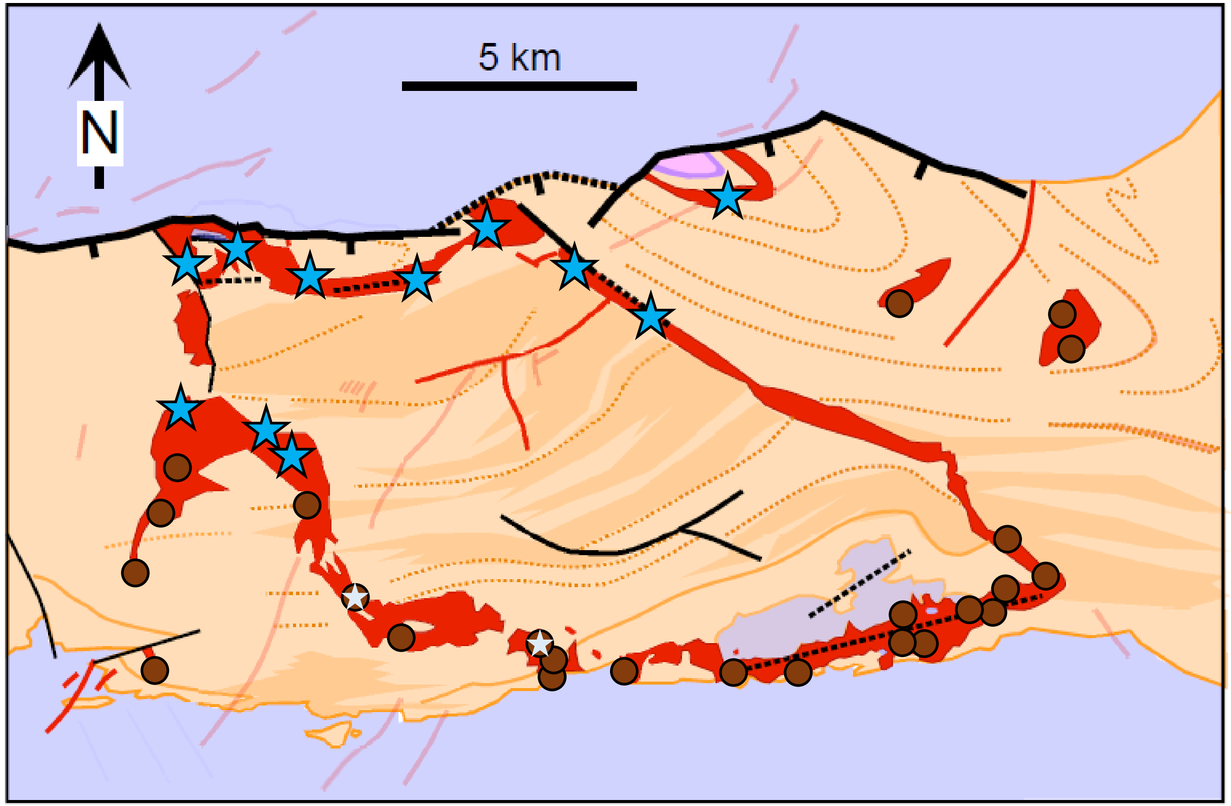
Fissure eruption on Kilauea lower East Rift Zone, 19 May 2018, USGS



Kamoamoa fissure eruption, 3/6/2011, USGS

Asymmetric Distribution of Igneous Rock Types and Asymmetric Intrusion – what is the connection?





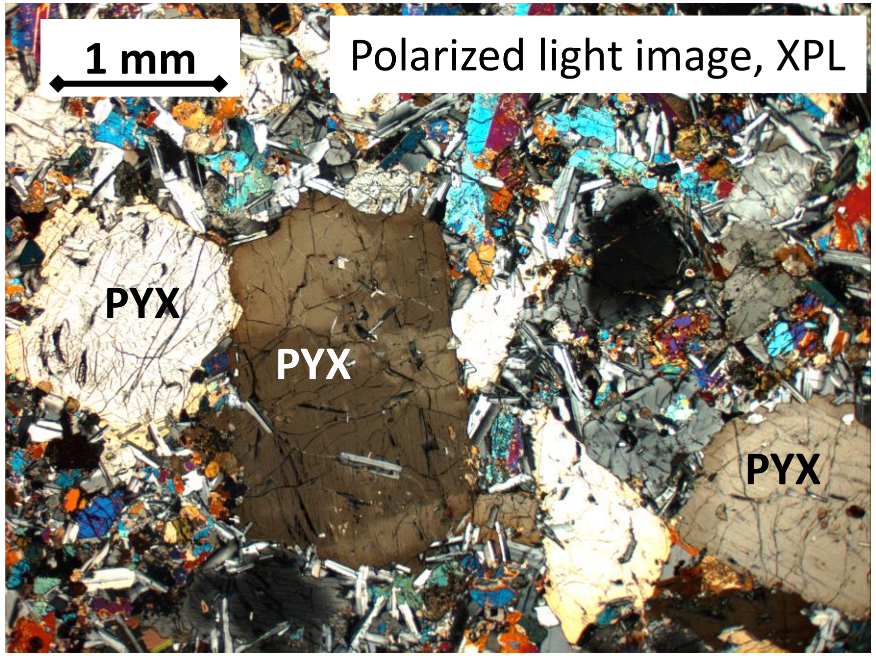
Previous workers noted asymmetric distribution of rock types, lack of mass balance in vertical cross-sections

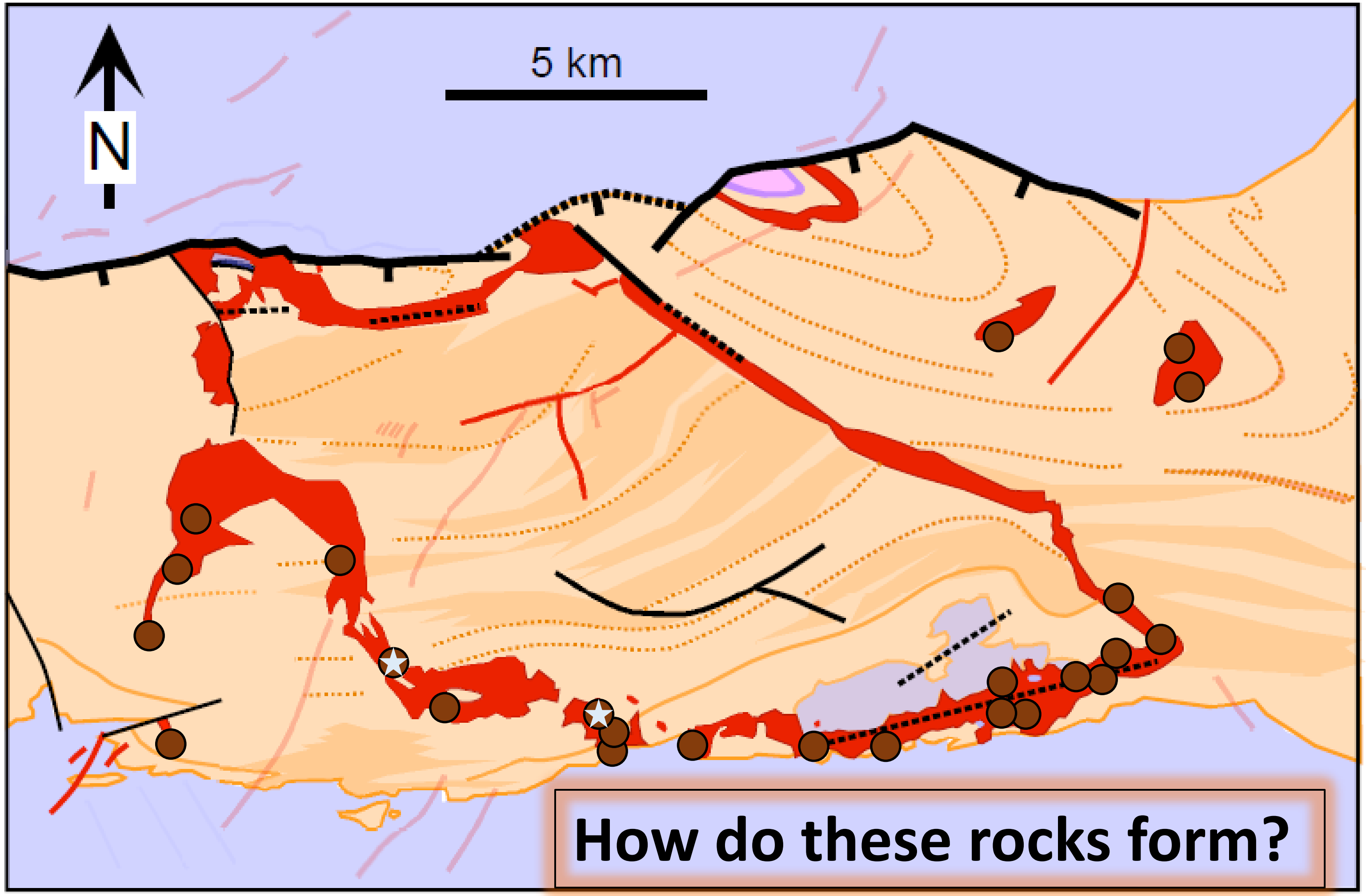
Smith, 1973; Smith et al., 1975; Mangan et al., 1993; Woodruff et al., 1995; Froelich and Gottfried, 1999; Husch, GSA Special Paper, 1992

Brown circles: diabase with accumulated pyroxene crystals (larger than matrix)

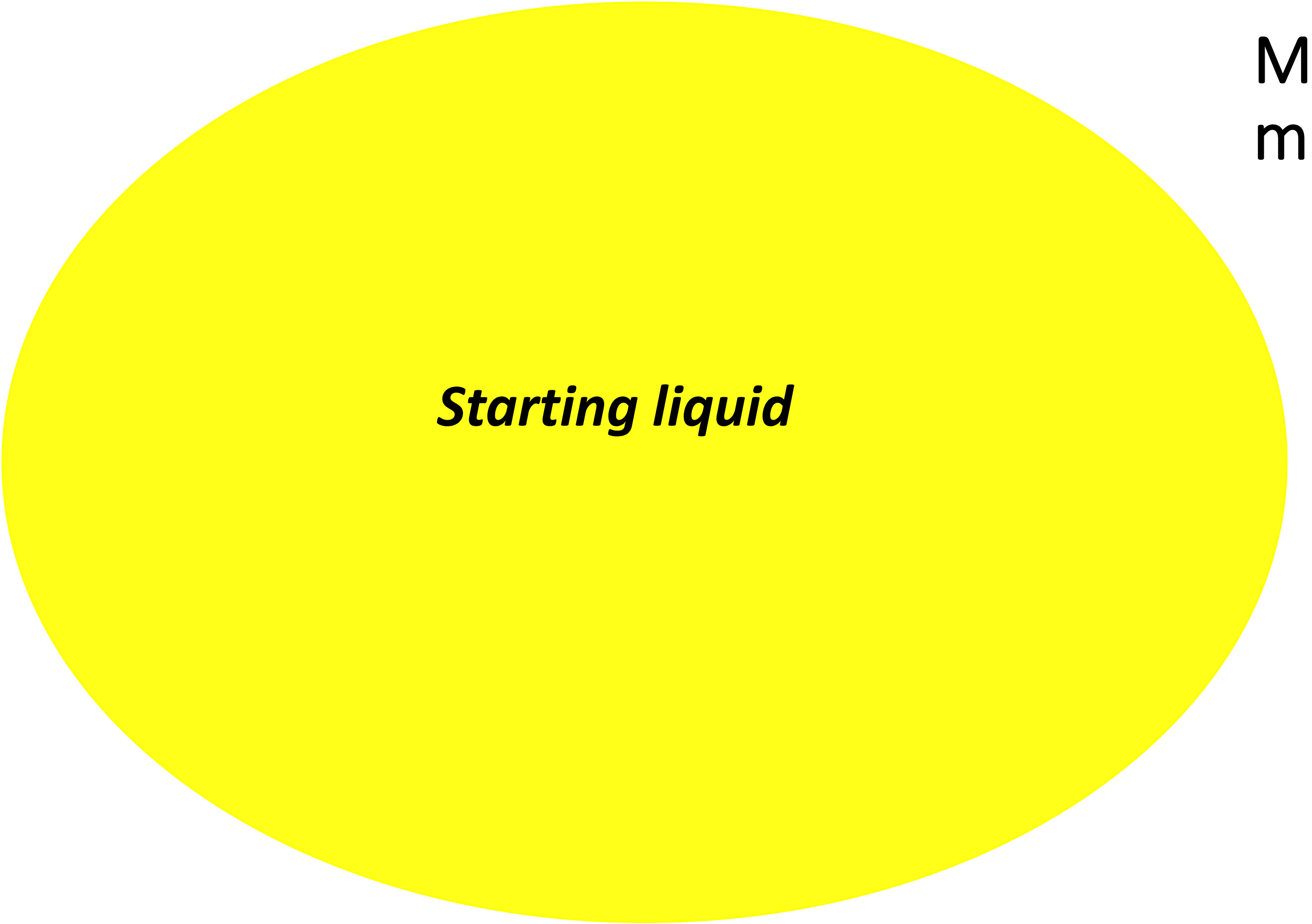
Blue stars: more evolved diabase with more abundant magmatic hydrothermal alteration

Accumulations of Pyroxene Crystals (larger than matrix crystals) – found in Deeper Segments, and Mostly in Sills





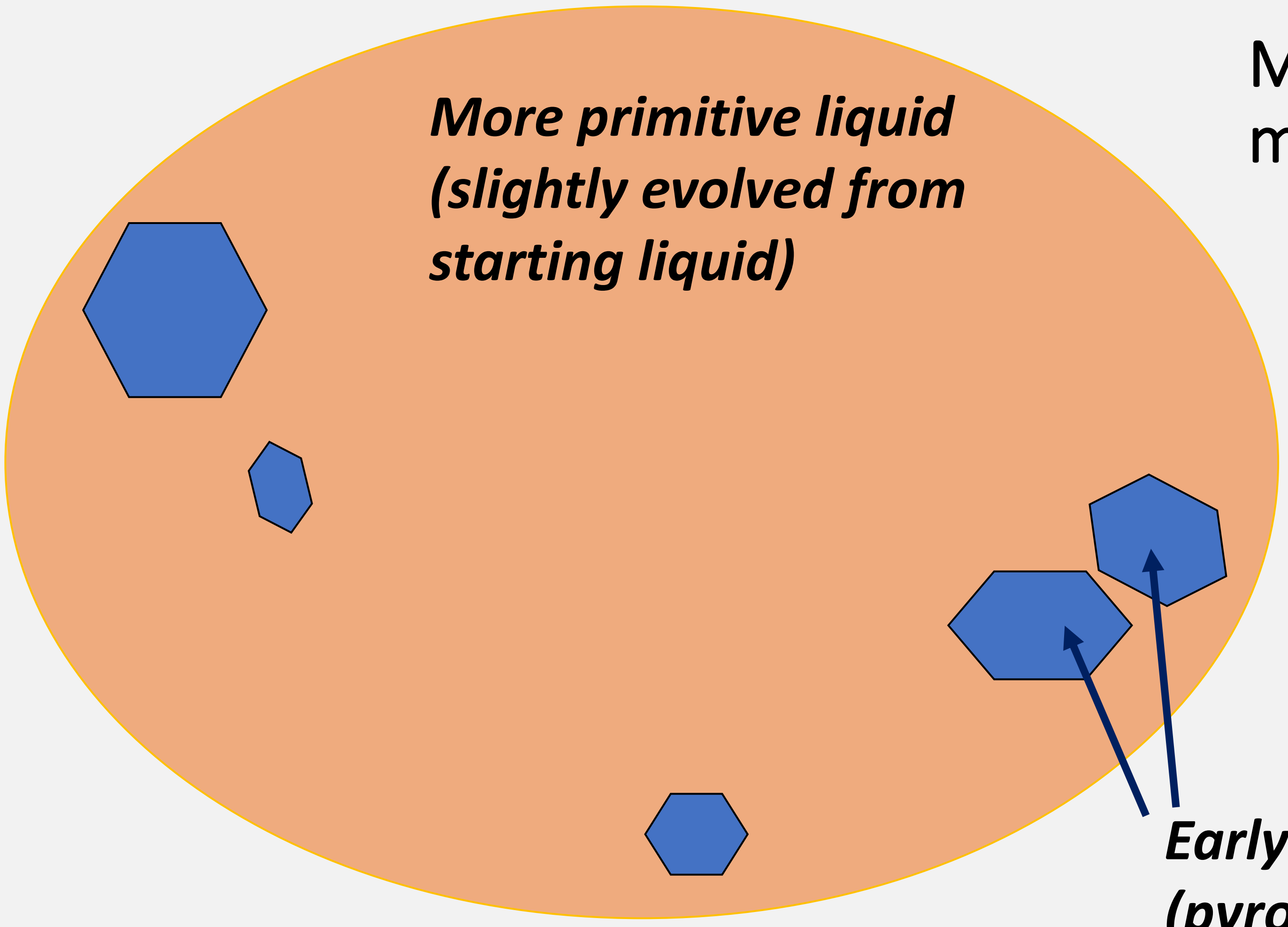
Accumulations of Pyroxene Crystals Found in Deeper Segments and Mostly in Sills



Magma crystallizes a sequence of minerals and changes composition

The starting liquid has the most ***primitive composition***

Accumulations of Pyroxene Crystals Found in Deeper Segments and Mostly in Sills



Magma crystallizes a sequence of minerals and changes composition

The magma changes composition (the magma ***evolves***) as crystals form

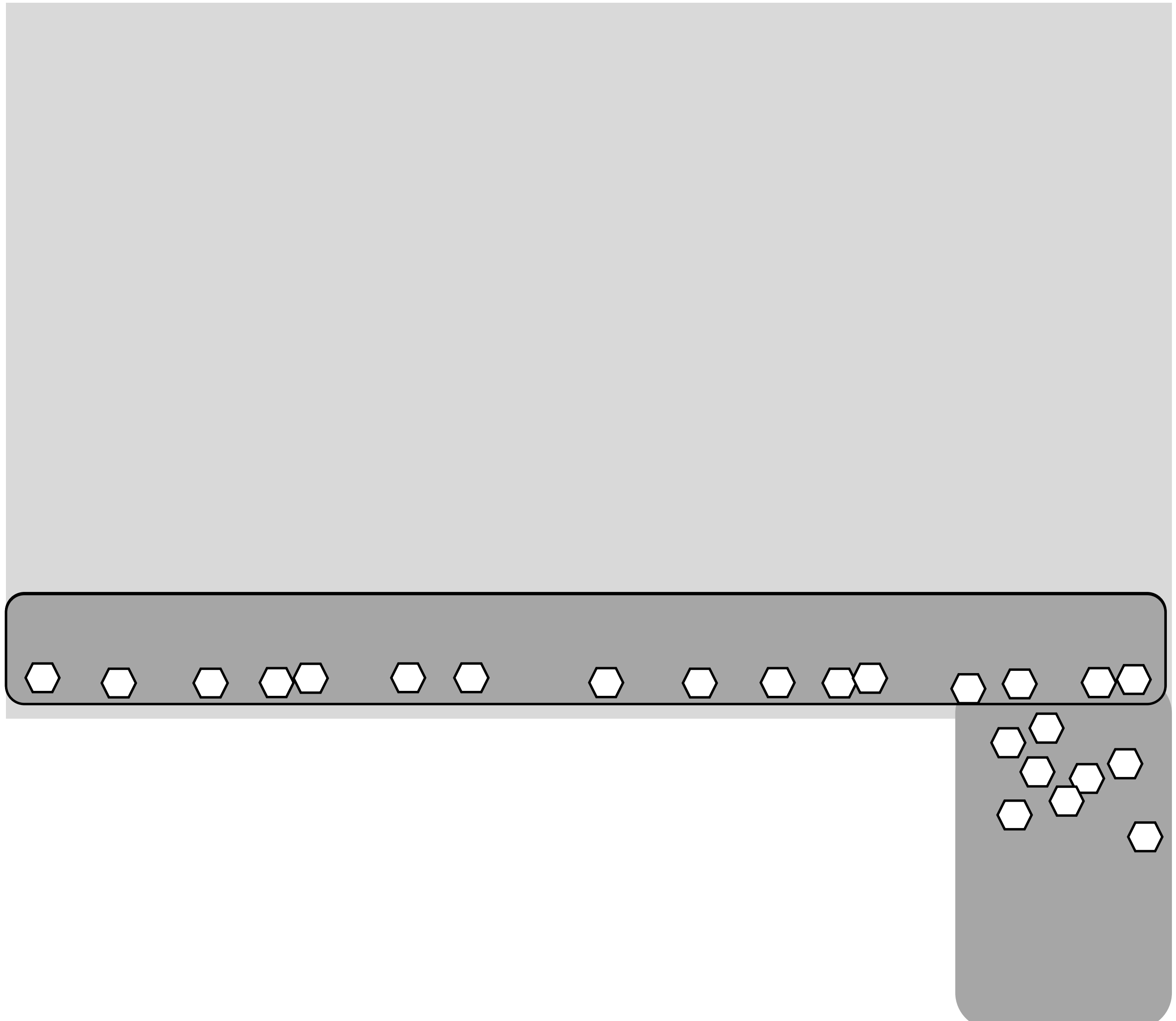
Accumulations of Pyroxene Crystals Found in Deeper Segments and Mostly in Sills

Magmas carry crystals that grew at deeper levels of the plumbing system

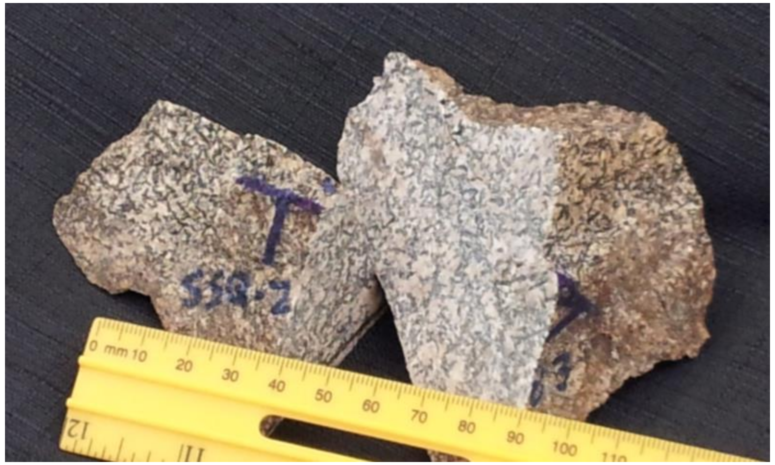
Early-formed crystals brought into intrusion by the magma can be mechanically sorted or re-distributed in the pluton

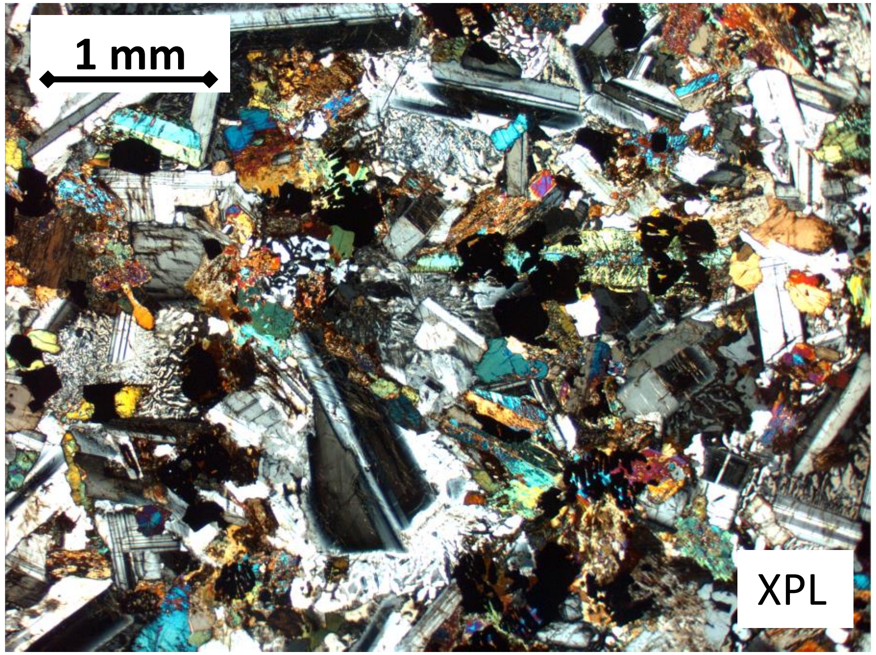
This explains occurrence of early-formed pyroxene crystals in the deeper, sub-horizontal segments of the intrusion

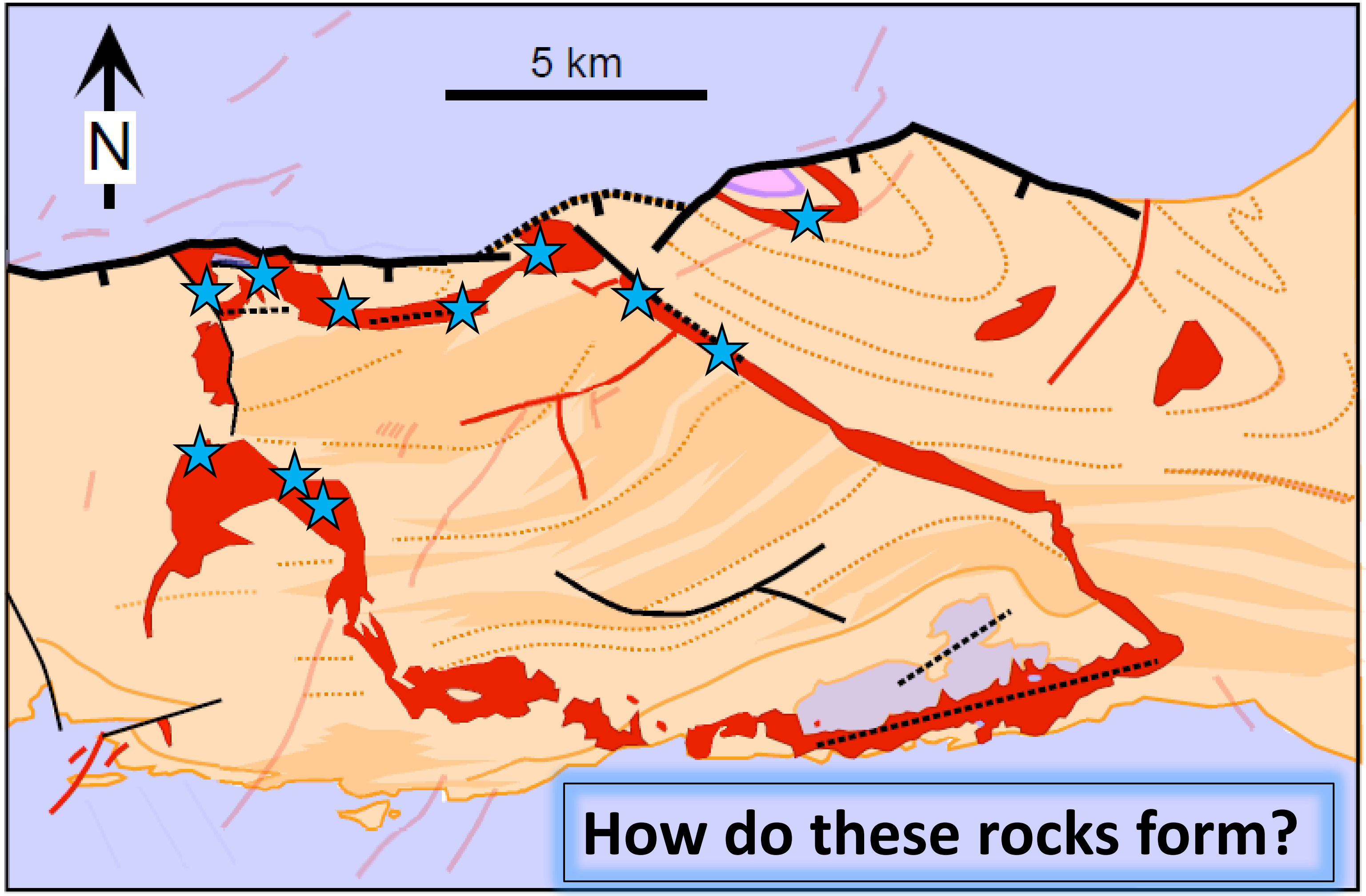
These ideas are not new, see:
Mangan et al., 1993; Woodruff et al., 1995; Froelich and Gottfried, 1999



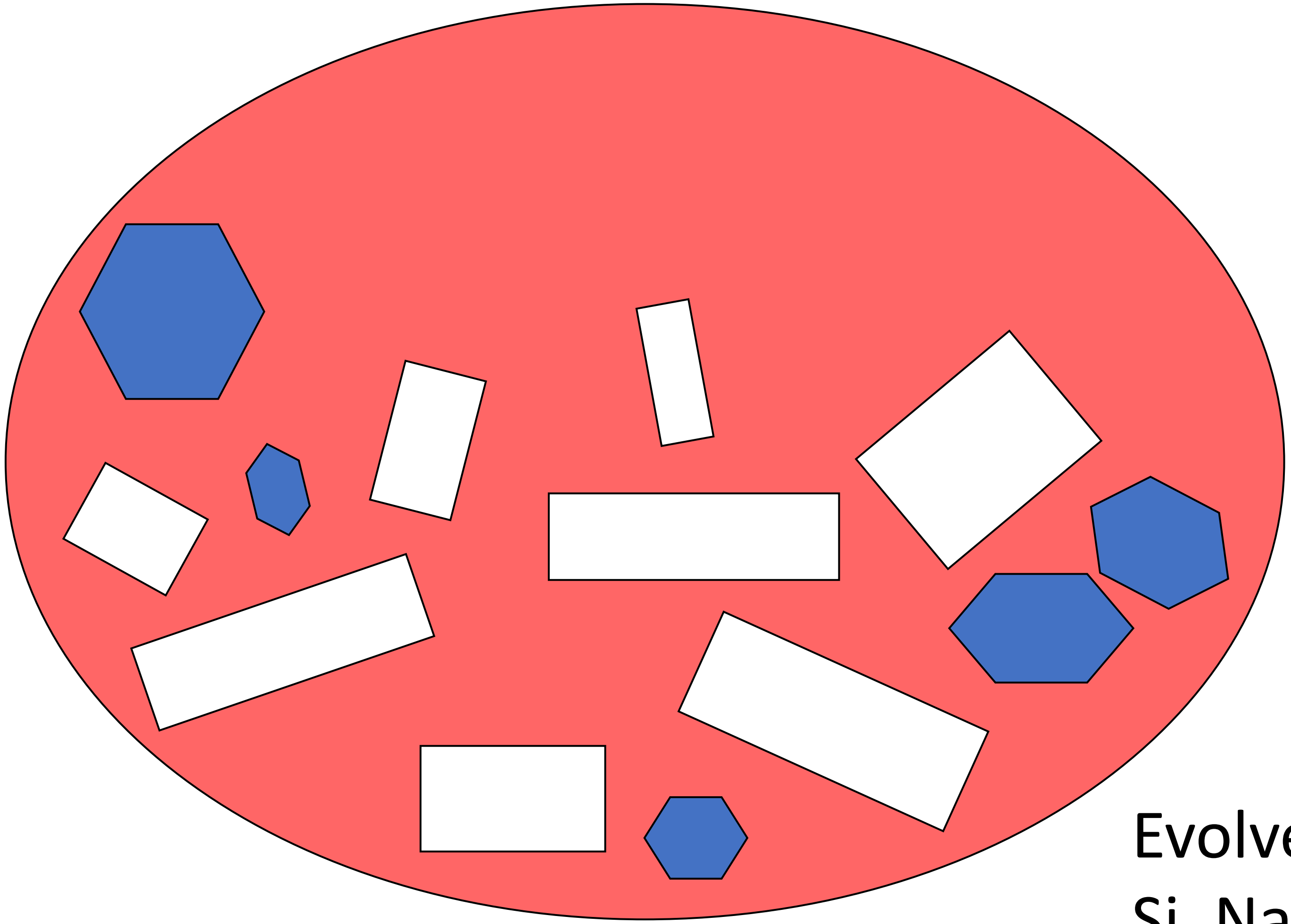
Evolved Igneous Rocks and Hydrothermal Fluid Alteration
Shallow Segments, Sill Roof Zones, and Dike Segments







Magma Evolves by Crystallization as Temperature Decreases



Different Minerals Grow

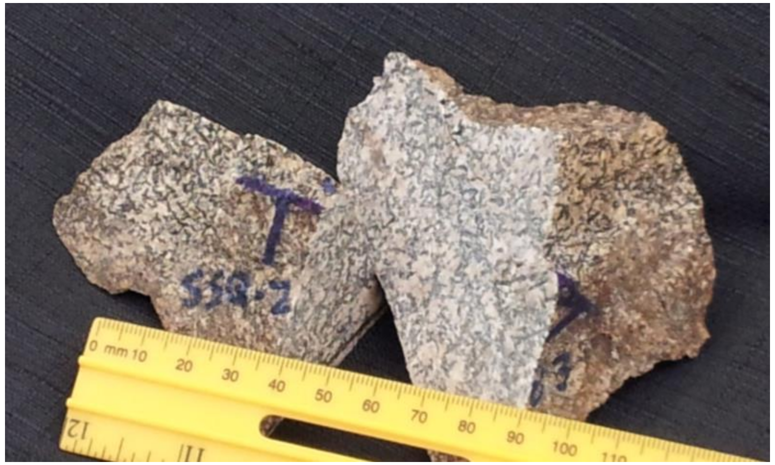
Liquid Composition Changes –

Liquid has a more ***evolved composition*** *as it crystallizes*

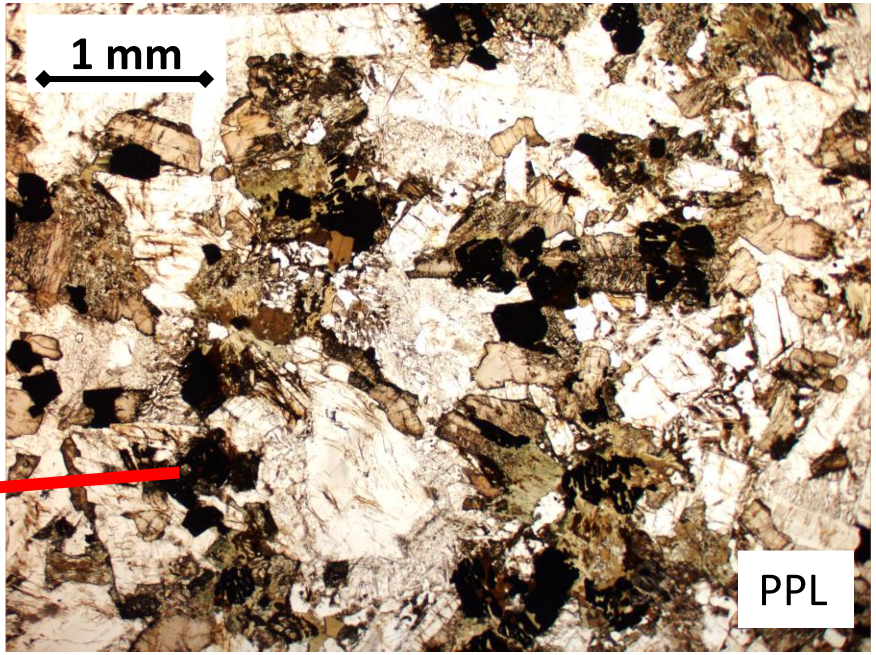
Evolved Magmas: high concentrations of Si, Na, K, Fe, H_2O (fluids)

Crystallize quartz, K-feldspar, Fe-Ti oxides; alteration by fluids

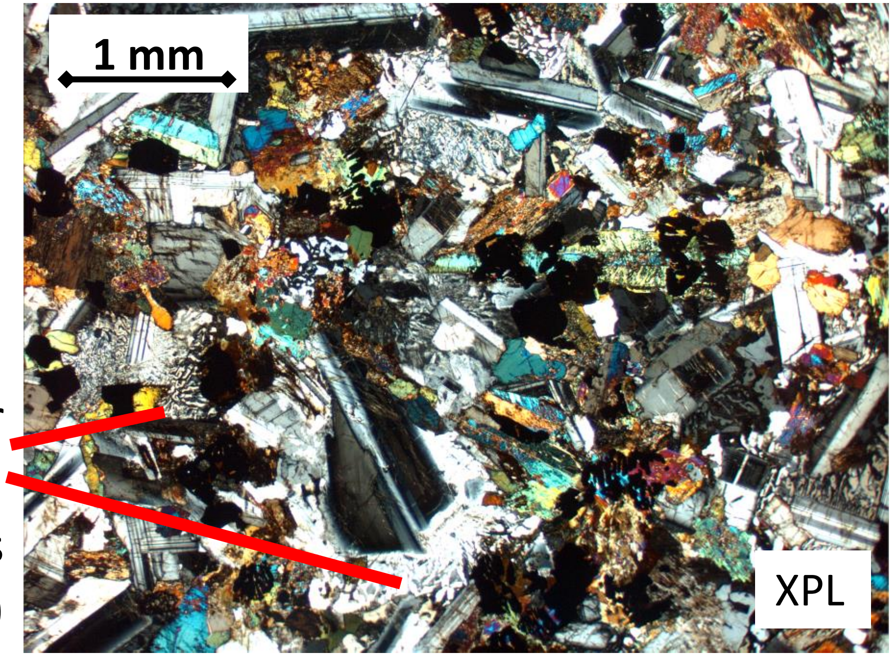
Evolved Igneous Rocks and Hydrothermal Fluid Alteration in Morgantown-Jacksonwald Complex



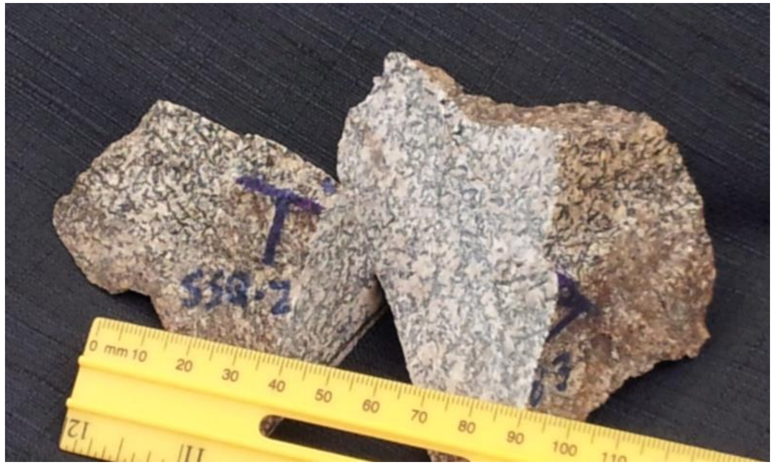
Fe-Ti oxides
(ilmenite, magnetite)

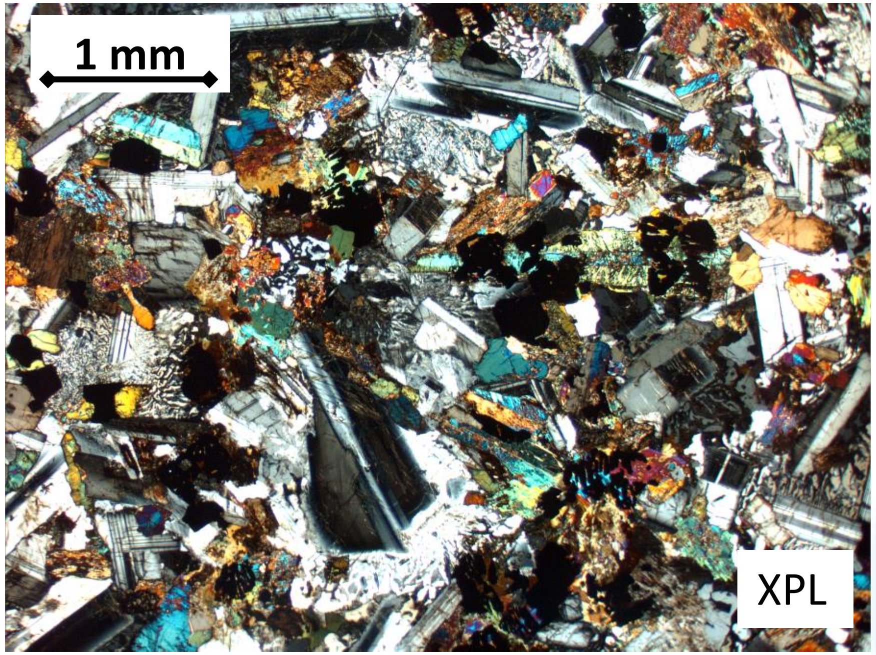


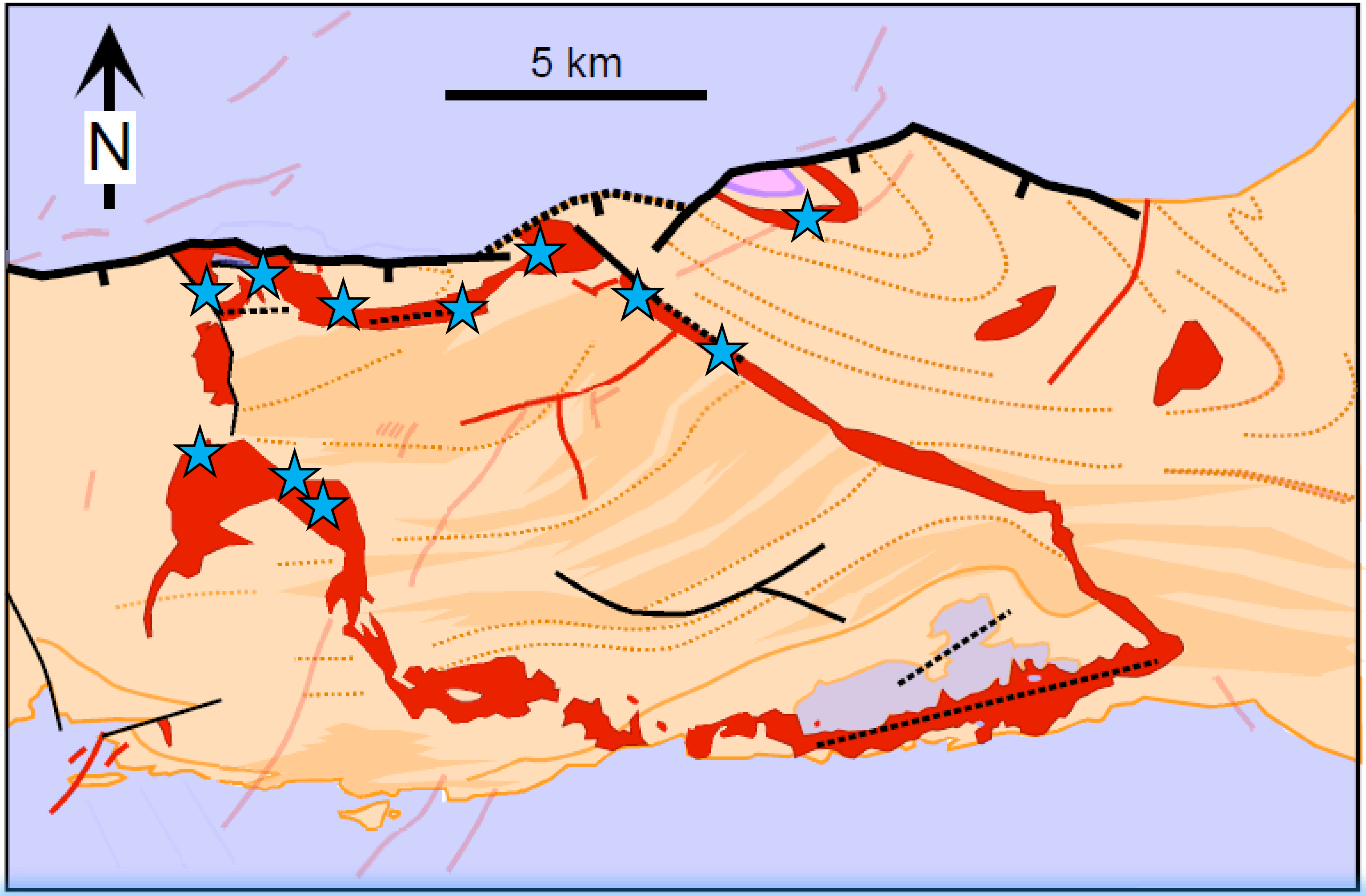
quartz and K-feldspar
(separate crystals and
quartz-feldspar intergrowths
called *granophyre*)



Evolved Igneous Rocks and Hydrothermal Fluid Alteration
Shallow Segments, Sill Roof Zones, and Dike Segments



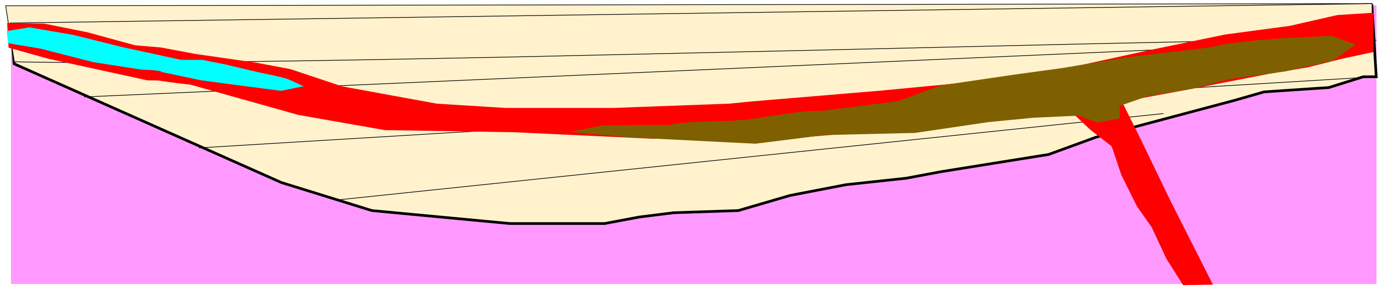


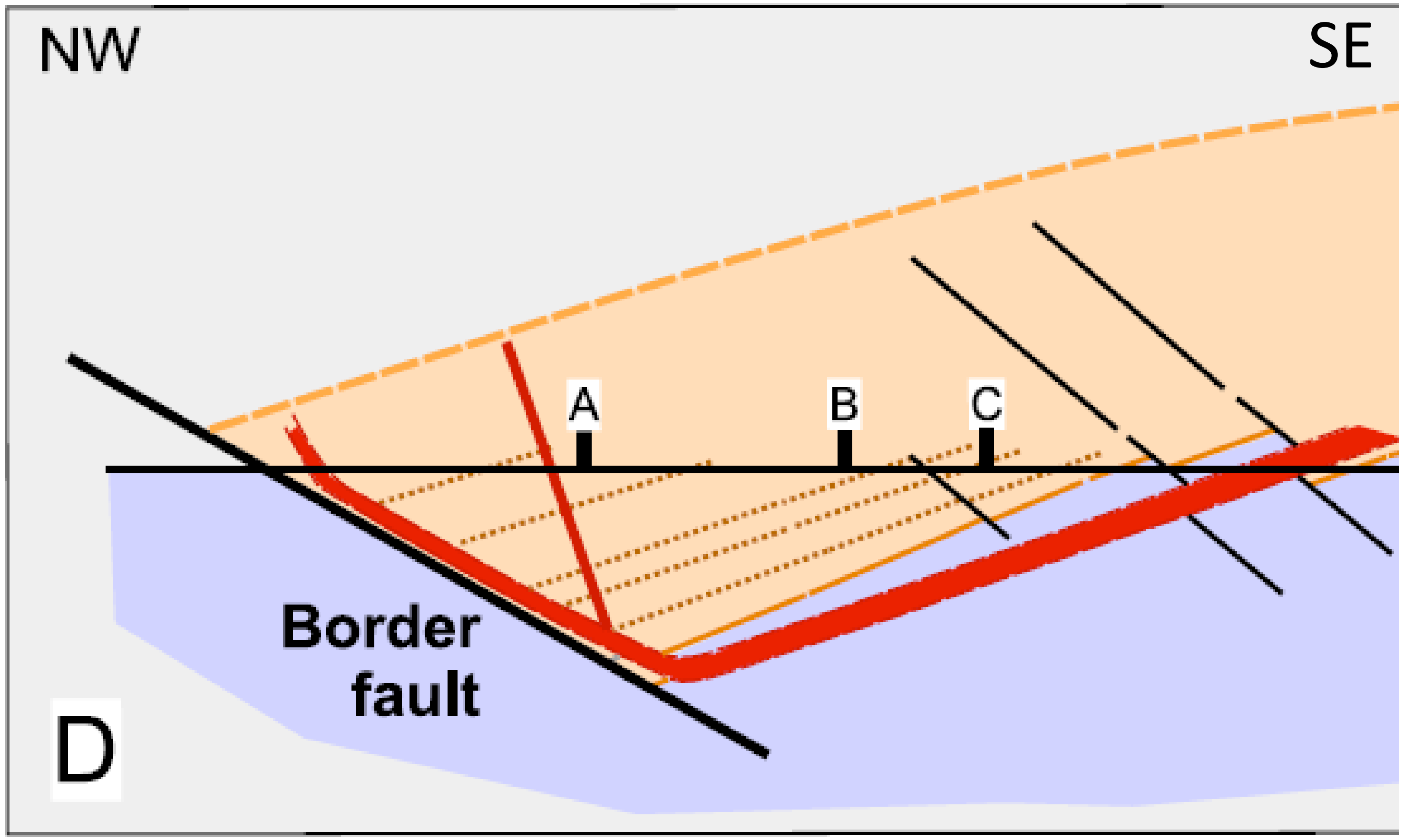


What is the Significance of these Rocks?

Previous Work: Assumed Saucer Shape for Intrusions

(Smith, 1973; Mangan et al., 1993; Woodruff et al., 1995; Froelich and Gottfried, 1999)



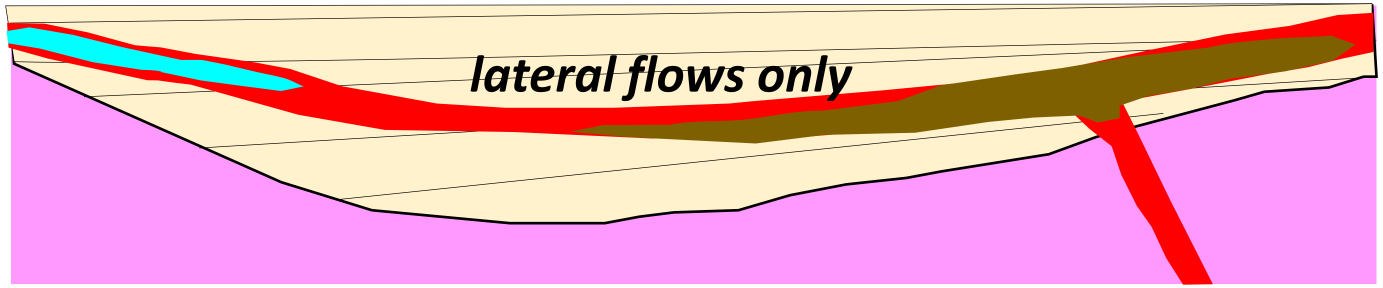


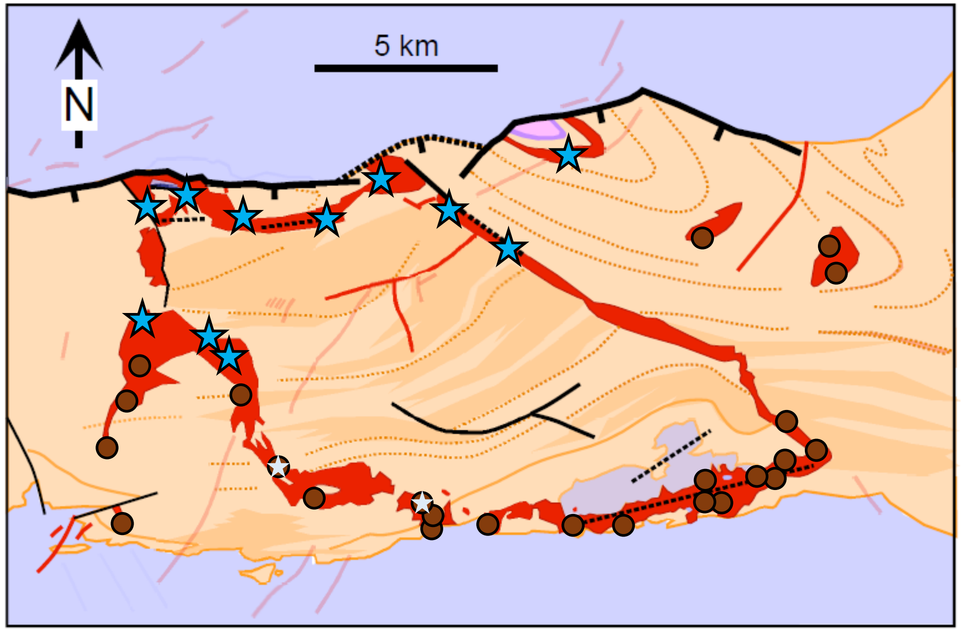
Without correcting for tilting and folding, shape looks like a symmetric saucer with SE and NW ends at about the same emplacement depth

<u>Model of lateral flow differentiation</u>

- Magma enters from feeder on SE side, crystals accumulate
- Magma flows down then up dip
- Magma evolves by fractional crystallization during lateral flow
- Evolved magma and hydrothermal fluids accumulate in up-dip section in NW
- **NO VERTICAL FLOWS**

PROBLEMS with Model of ONLY Lateral Flow



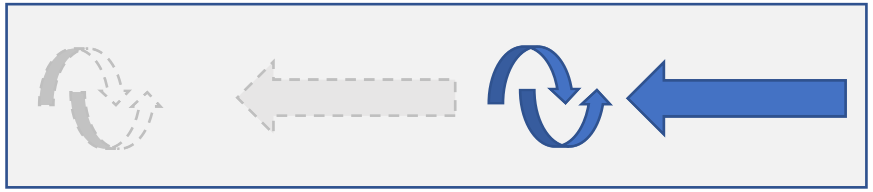


Flow in Sills and Sub-horizontal Sheets, Saucers
<u>(Holness et al., 2017 and references therein):</u>

Convective flow mostly during emplacement

Once magma inputs stop, convective flow stops and no more lateral transport

Fractional crystallization occurs mostly AFTER emplacement, after most of lateral transport is done



Sill – convective flow during emplacement

Sills and sub-horizontal sheets accomplish lateral transport of magma, crystal sorting and distribution during emplacement

Upward migration of evolved liquid, fluids results in "sandwich zone" between floor and roof, not a laterally-displaced zone

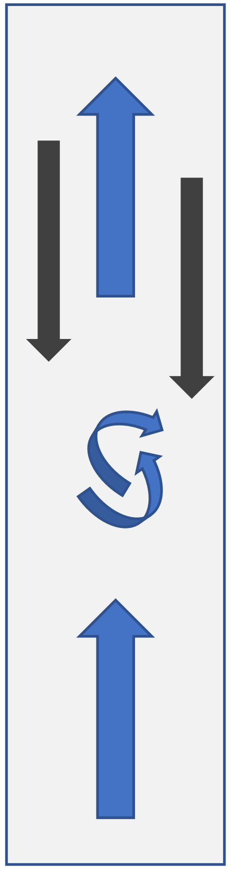
Reconstructed Shape of Intrusion: Importance of Vertical Flows

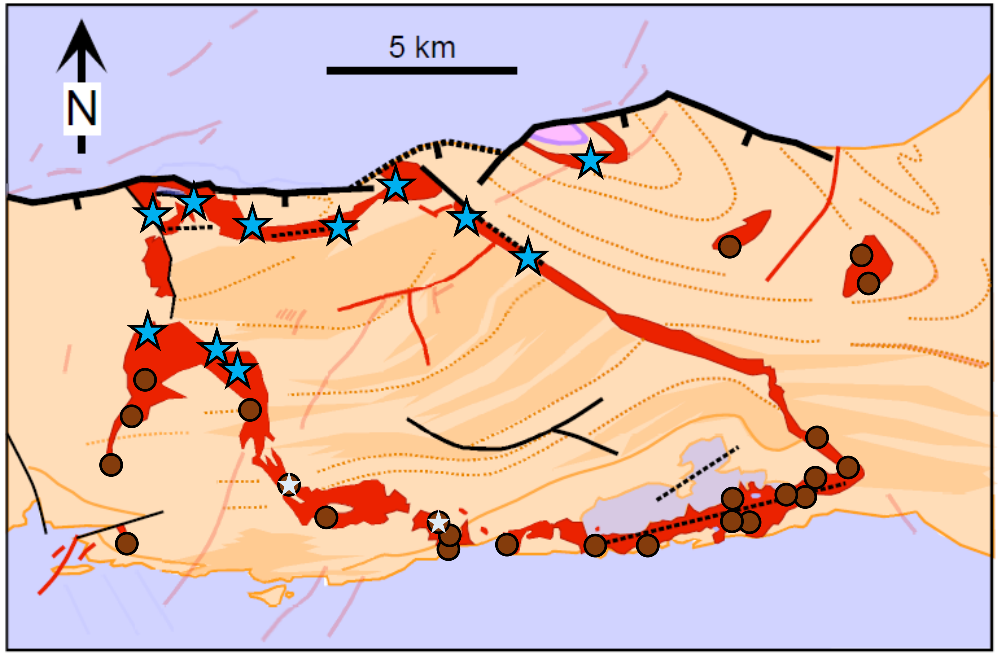
Flow in steeply-dipping sheets and dikes (Holness et al., 2017):

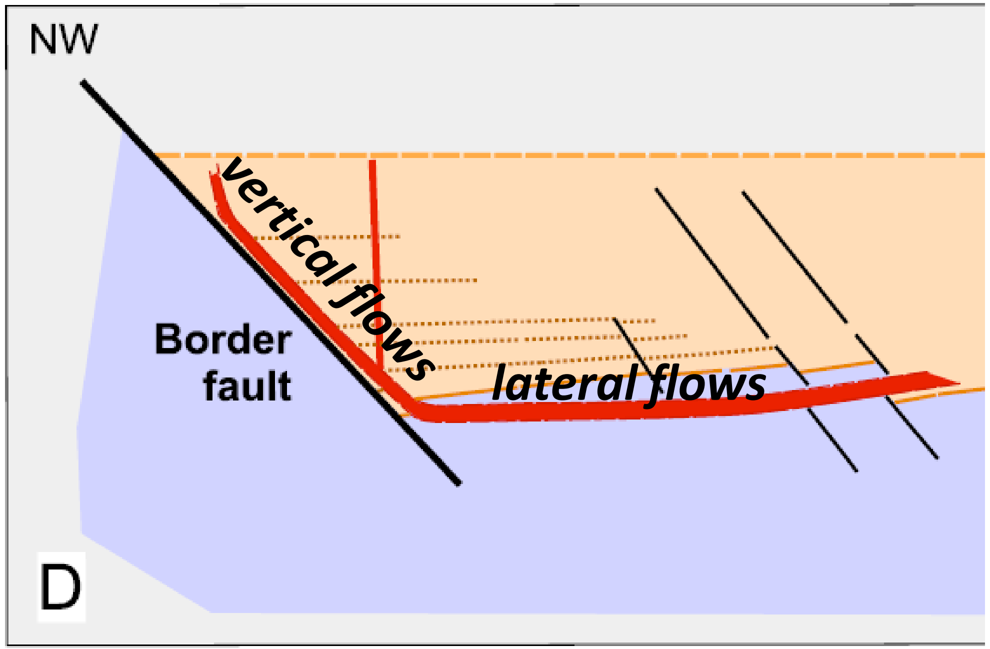
Convective flow continues after magma emplacement and inputs stop

Fractional crystallization occurs with vertical convection

Result is continued upward transport of evolved liquids & magmatic fluids







Dike segments transport magma more rapidly and promote degassing:

H_2O, CO_2, S-compounds → atmosphere

Conclusions:

Magma transport and flow within rift-basin plumbing system

- Shape of intrusion guides our interpretation of magma emplacement and flow
- Magma flow into deep sills → accumulated crystals; liquid moved toward dike segments
- Magma flows in steeply-dipping segments → efficient, rapid transport for basalt fissure eruptions, possibly enhanced degassing to atmosphere *(effects on living organisms?)*
- Improved model for crystal accumulation, liquid separation, fluids and gas release compared with model of lateral flow differentiation in a saucer sill

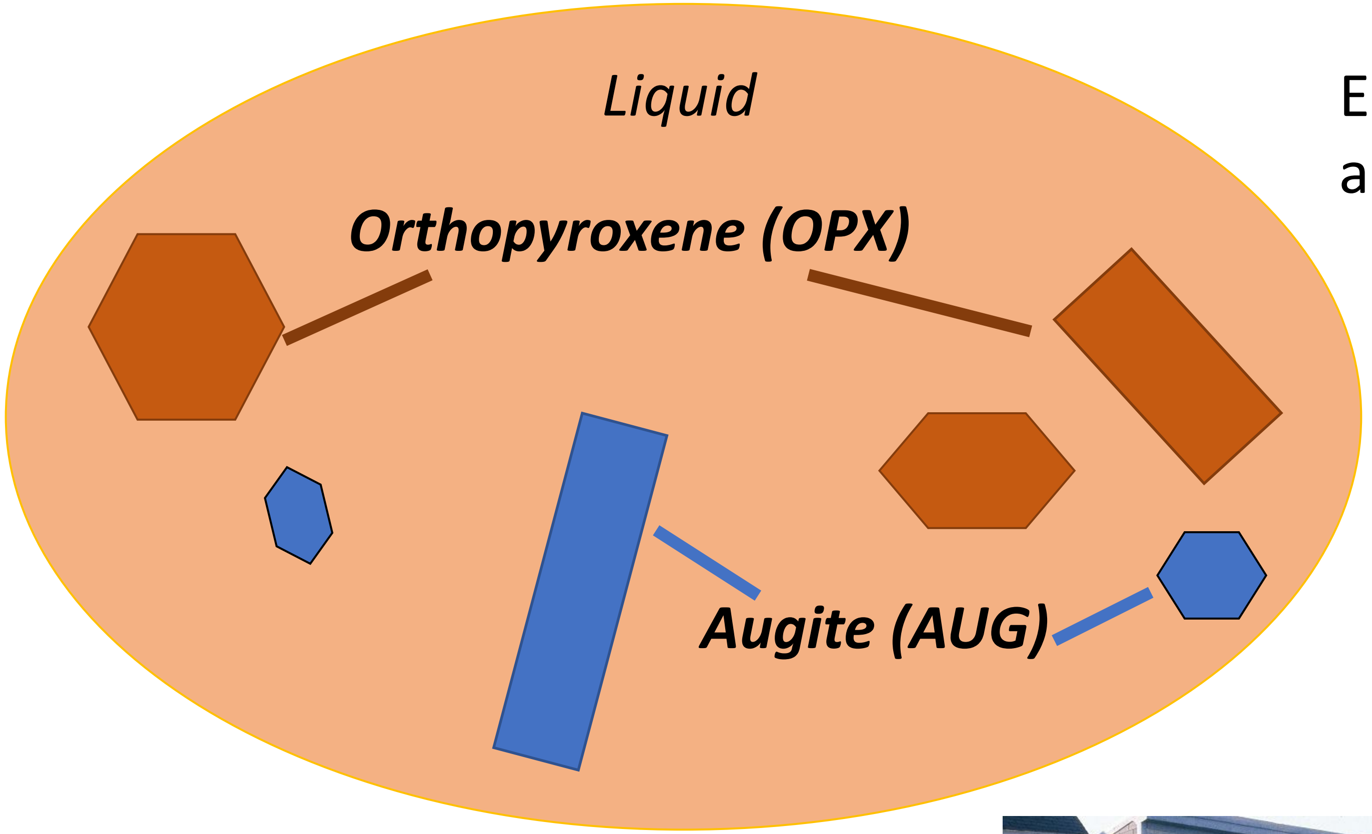
Importance of dike segments to transport magma rapidly to eruption –

Steeply-dipping dike segments were under-appreciated in previous models of rift basin intrusions

Outline of presentation

- CAMP plumbing system in the rift basin –
  previous talk by Martha Withjack
- Magma transport and flow within the rift-basin plumbing system
- CAMP plumbing system in the crust between the magma source region (upper mantle) and the rift basin (~ 8 to 40 km)
- Magma transport and flow in the trans-crustal plumbing system
  - **Petrologic evidence**
  - **Field evidence (existing geologic maps, Smith et al., 1975)**
  - **Seismic evidence (other studies in literature)**
  - **Geochemical evidence (other studies in literature)**

CAMP Plumbing System in the Crust: Evidence from Petrology

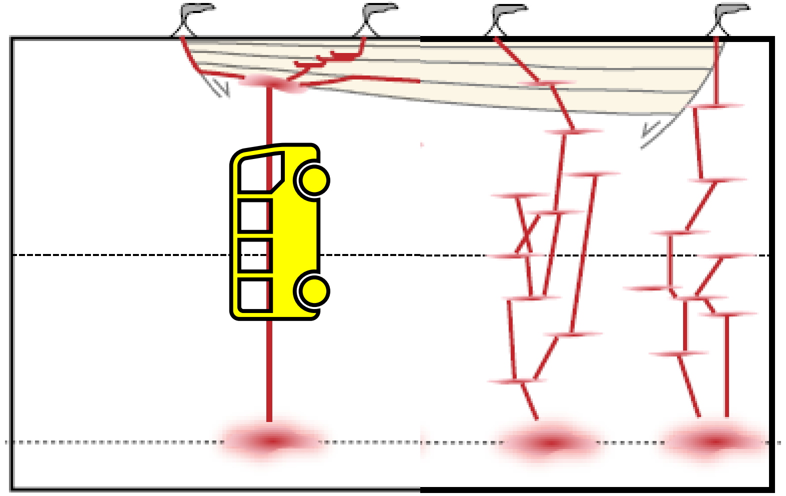


Early-formed crystals grew at deeper levels and were brought up into rift basin

Early-formed **Pyroxene** of 2 types**:**

- **Orthopyroxene (OPX), low-Ca**
- **Augite (AUG), high-Ca**

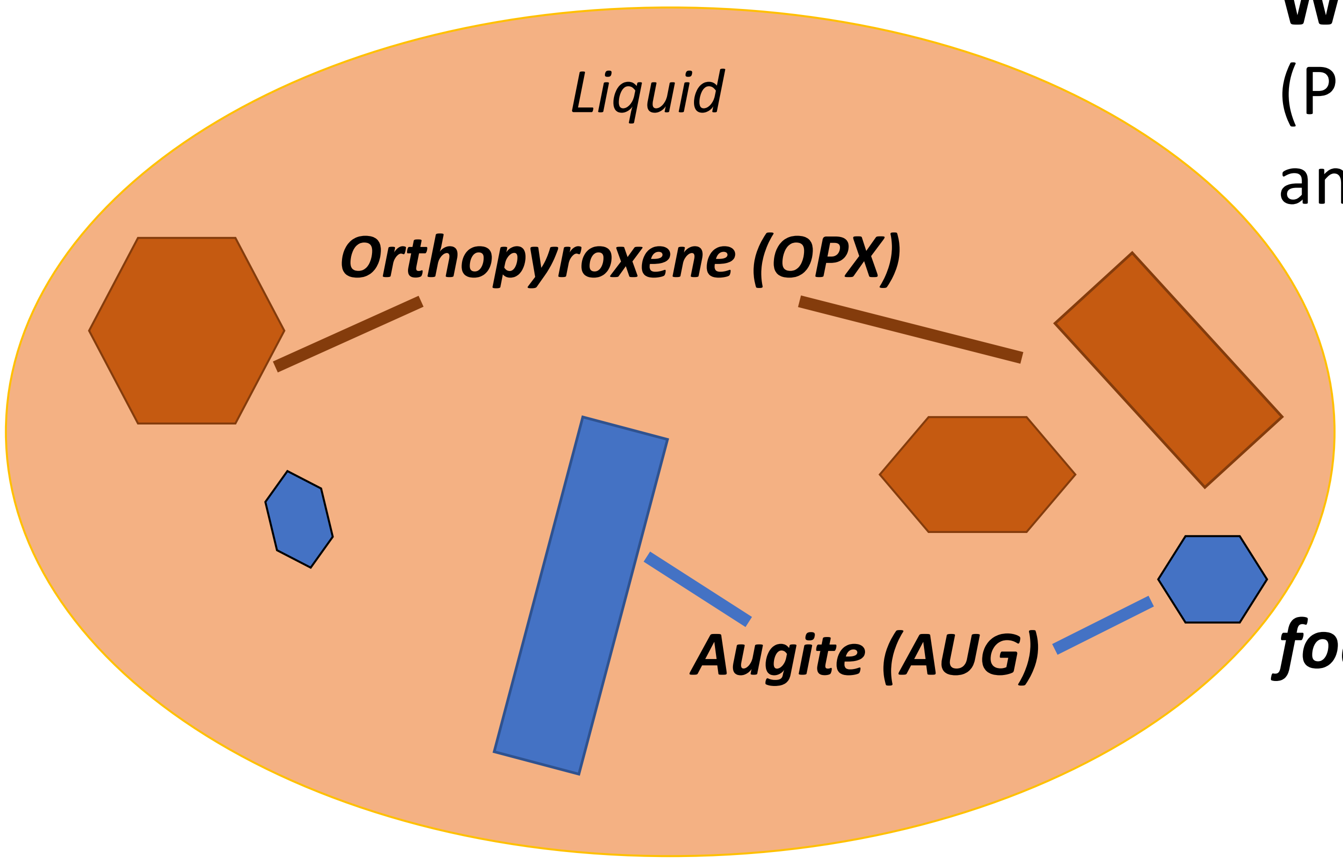
Image source: Magee et al., 2016



What can early-formed crystals tell us about the deeper plumbing system?

- What kind of transport network?
- What combination of sills and dikes/ramps?

CAMP Plumbing System in the Crust: Evidence from Petrology



We use Thermobarometer equations (Putirka RiMG 2008 for OPX; Neave and Putirka, AmMin 2017 for AUG):

to estimate ***temperature*** and ***pressure (depth)*** at which pyroxene crystals grew

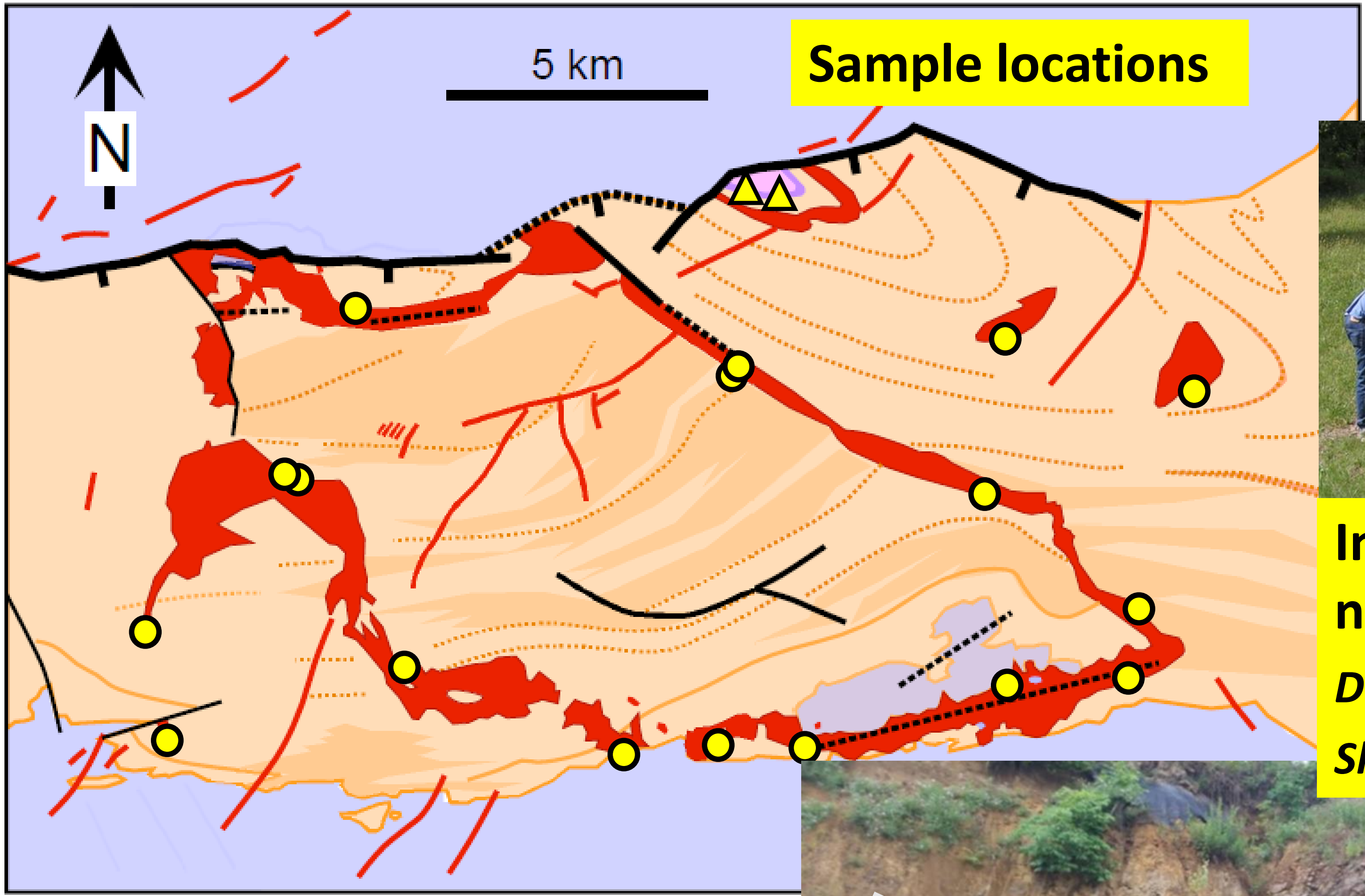
focus on early-formed crystals, cores –

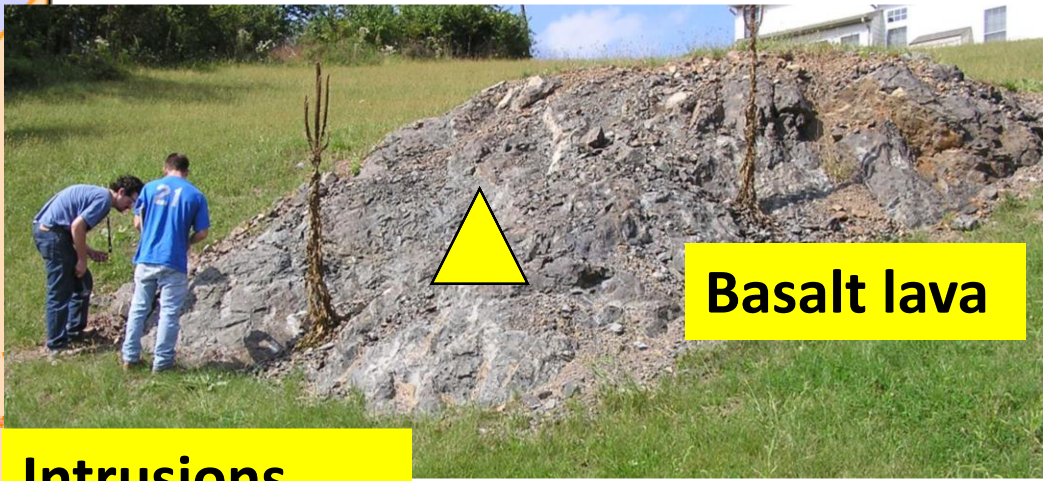
in equilibrium with more primitive liquids (basalt, chill margin diabase)

Previous P-T estimates using thermobarometry: Callegaro et al., 2013, Capriolo et al., 2020

OUR WORK: first PT values for OPX in CAMP; first PT values for CAMP using updated Neave and Putirka (2017) barometer for AUG

Sampling Across Rift Basin

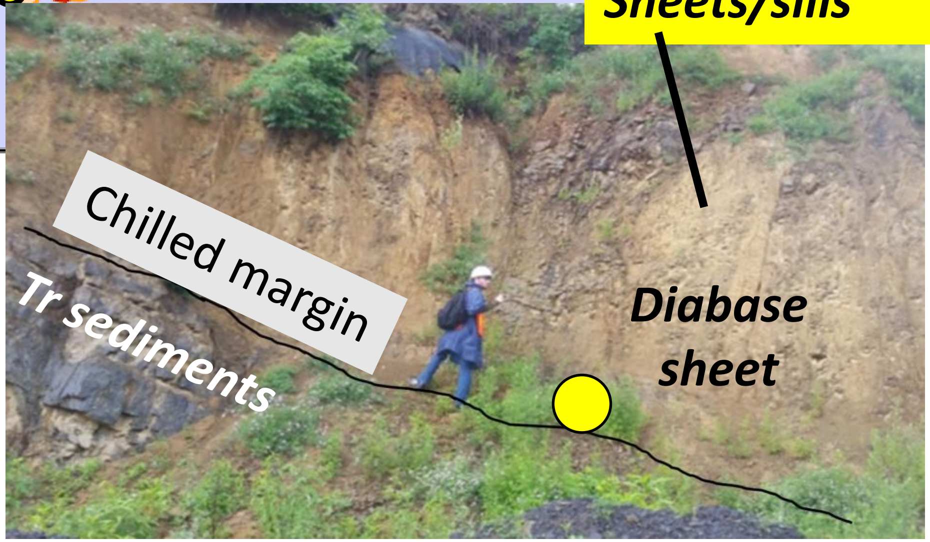


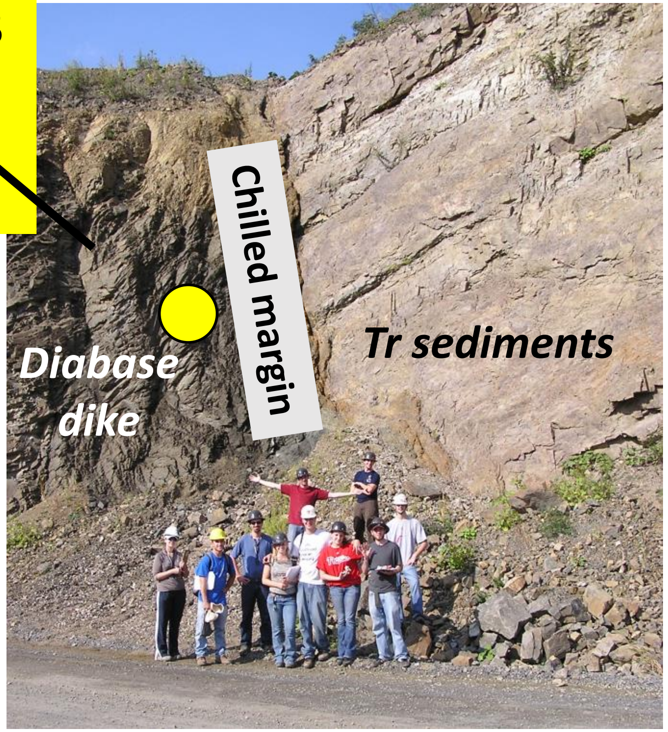


Intrusions near contacts

Dikes/ramps

Sheets/sills

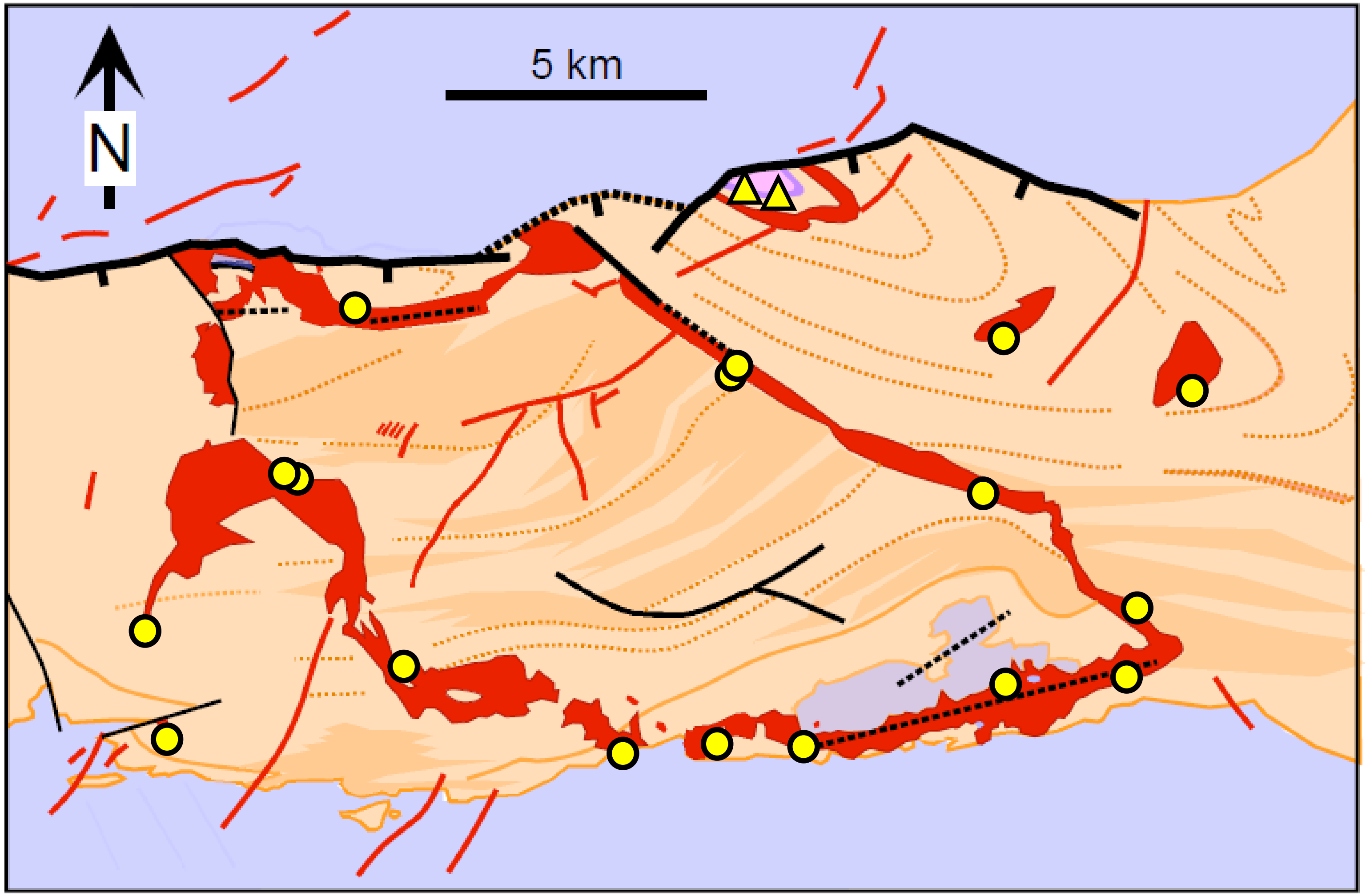




20 samples for P-T estimates

- OPX: 66 crystals
- AUG: 120 crystals

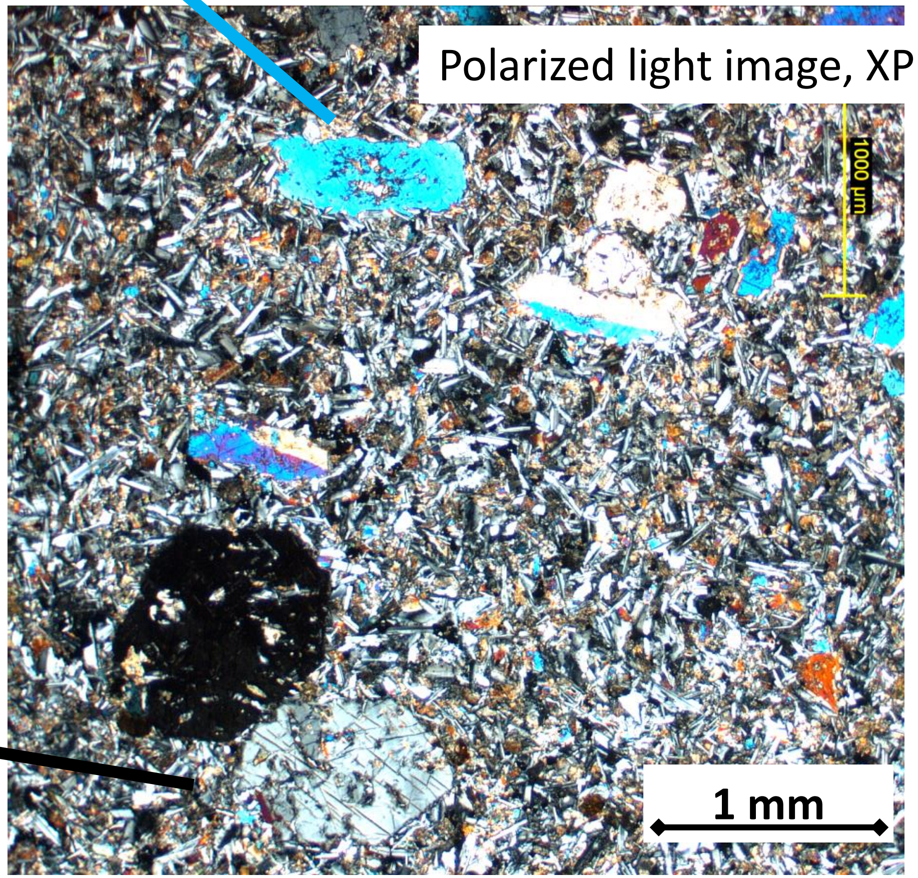
CAMP Plumbing System: Evidence from Petrology



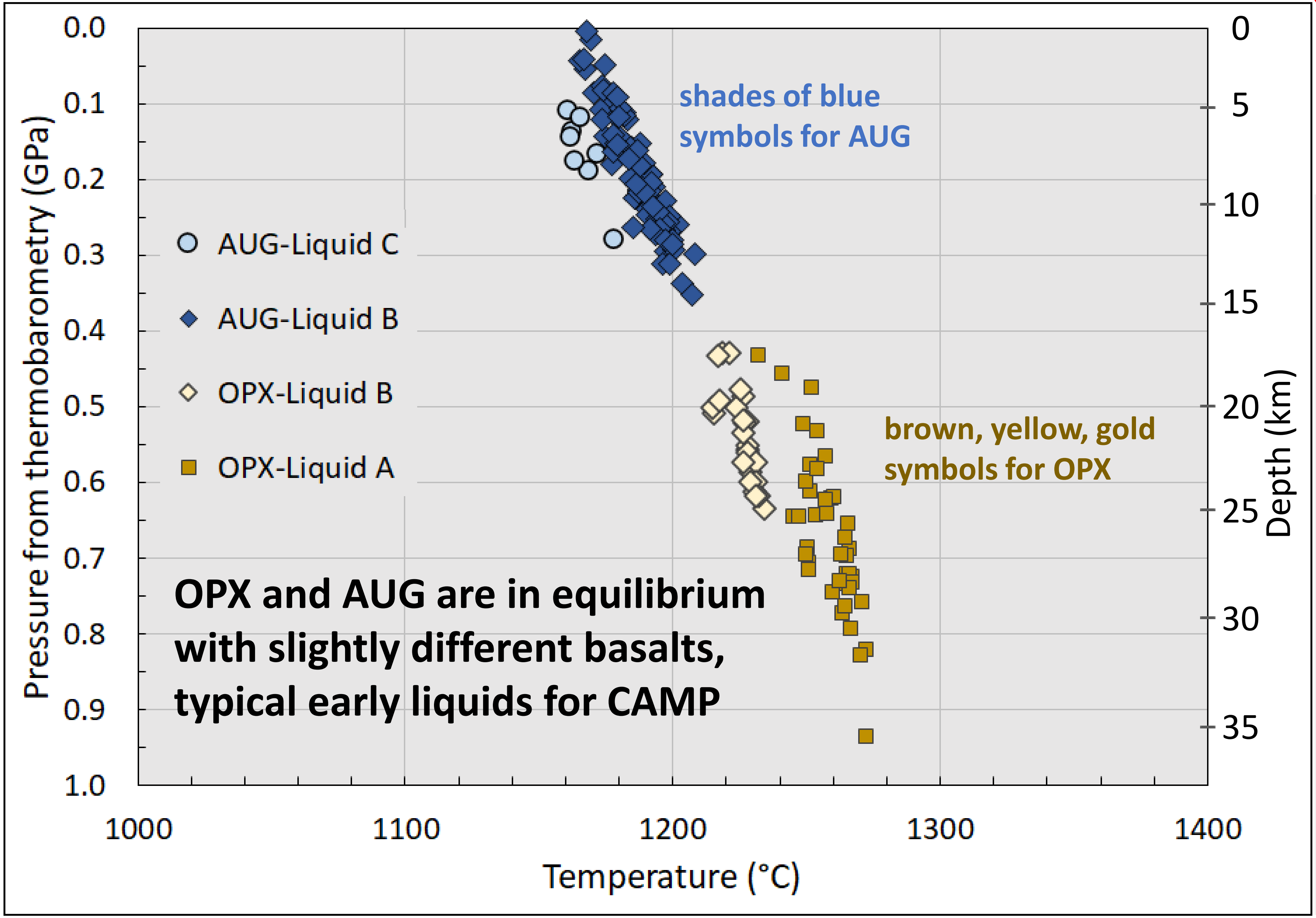
20 samples for P-T estimates

- OPX: 66 crystals
- AUG: 120 crystals

Crystals in thin section:



CAMP Plumbing System: P-T results



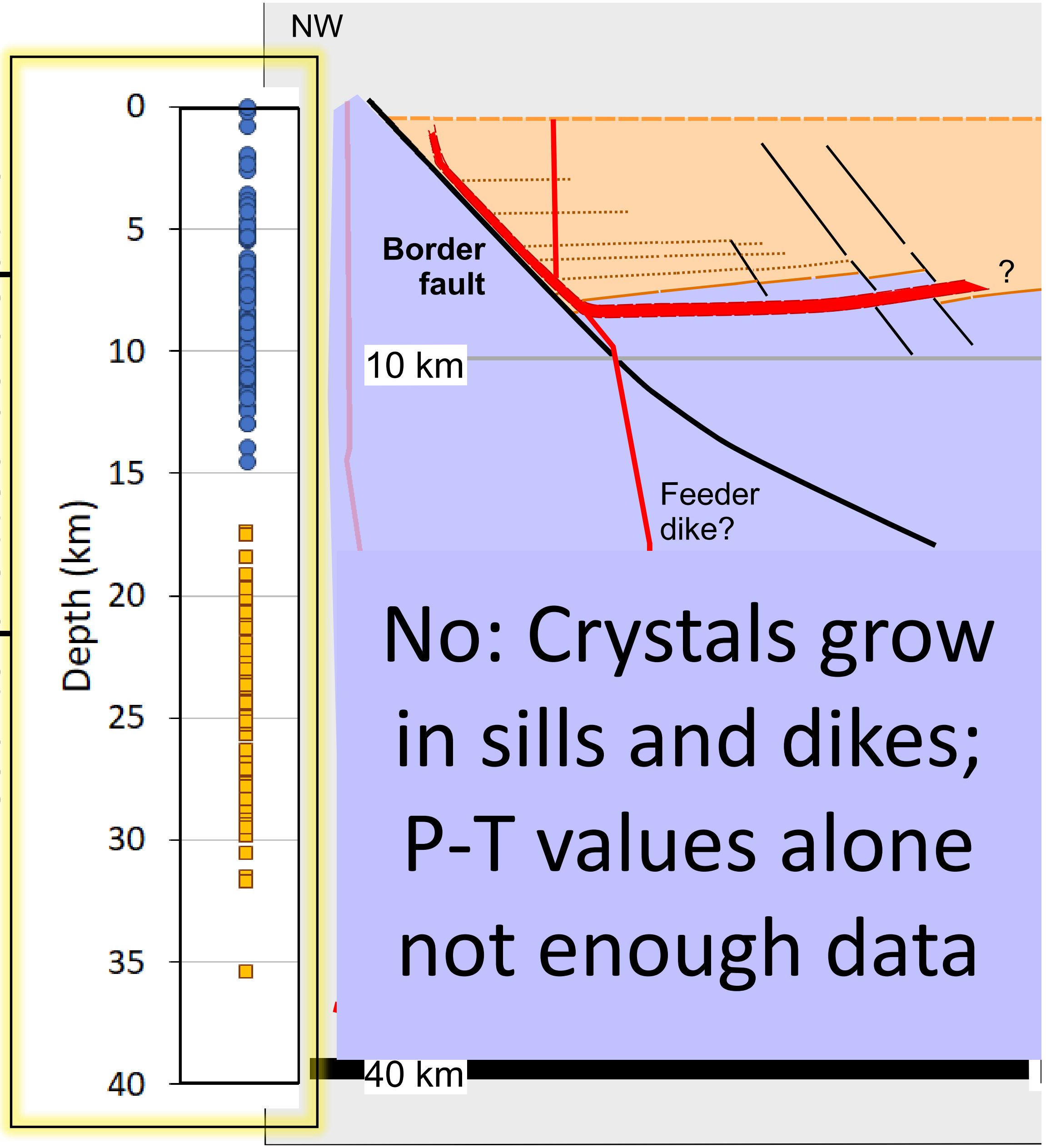
Multiple batches of similar basalt magmas in plumbing system

Crystals grew at all crustal levels but:
AUG: lower P (depth)
OPX: higher P (depth)

Probability that data are random sample of normal distribution = 8×10^{-28}

Do PT results (left) distinguish growth in sills vs. dikes?

P-T results plotted as depths



No: Crystals grow in sills and dikes; P-T values alone not enough data

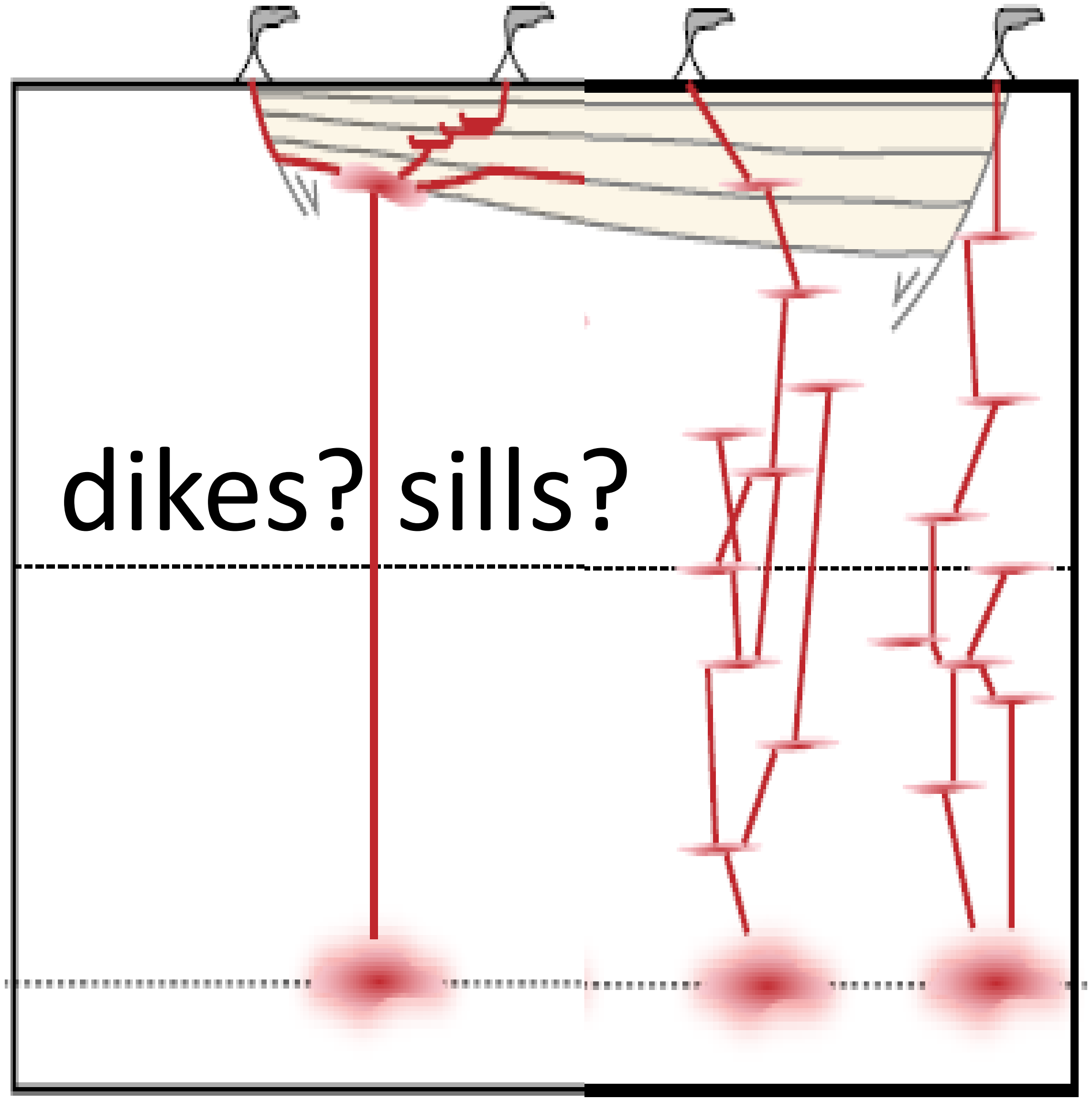
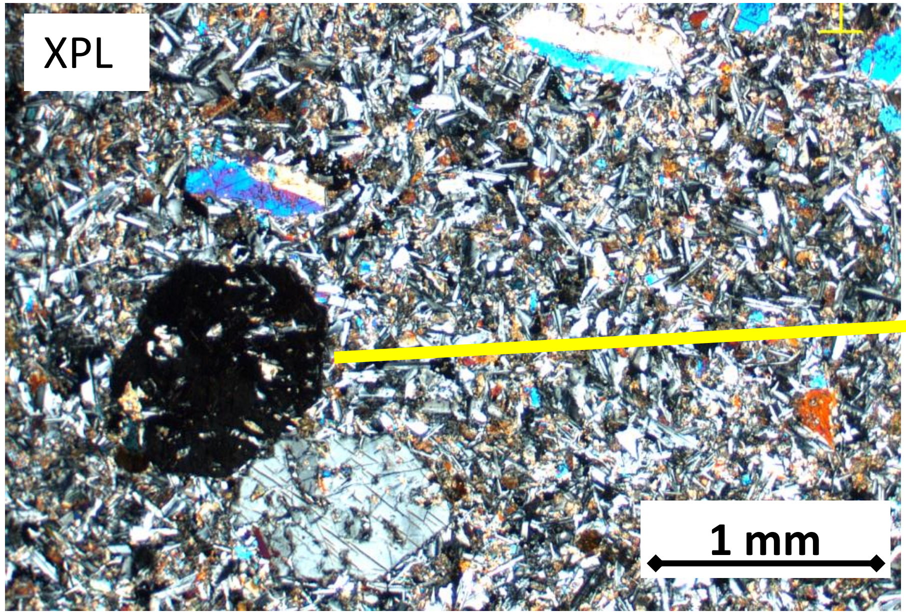
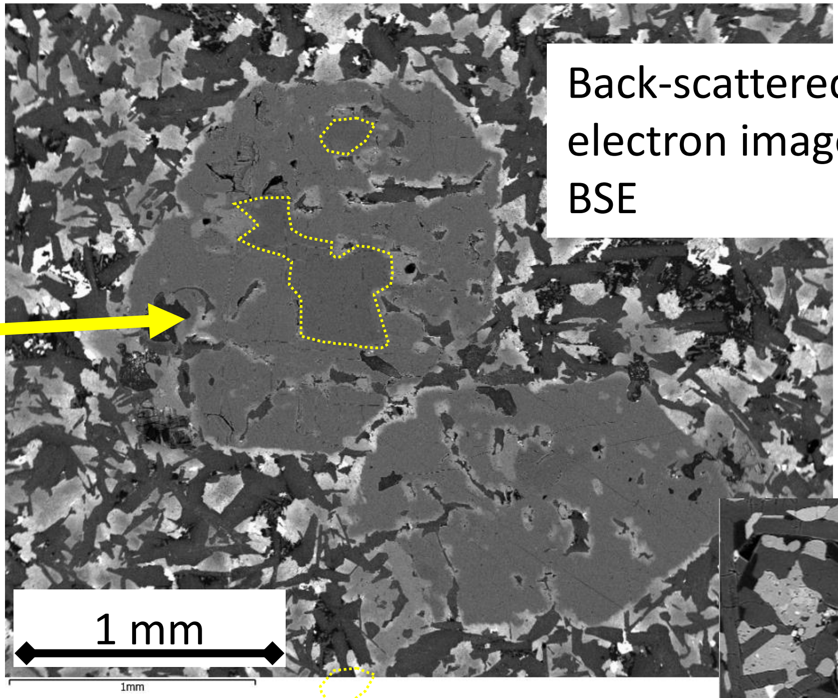


Image source: Magee et al., 2016

CAMP Plumbing System: Evidence from Crystal Shapes, Textures





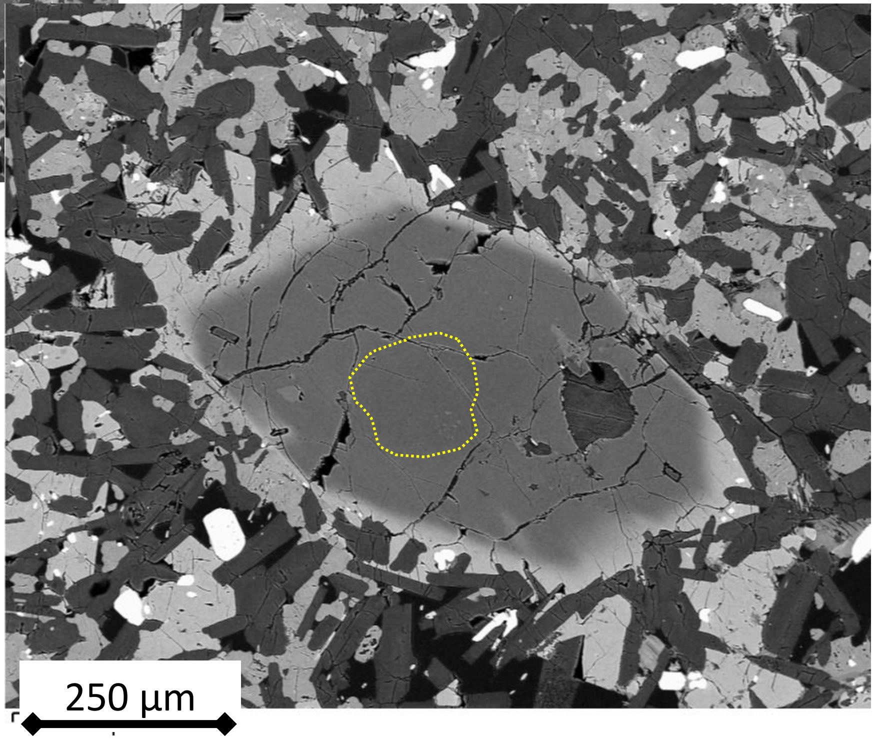
BSE images:

- Pyroxenes: medium to light gray
- Plagioclase: dark gray

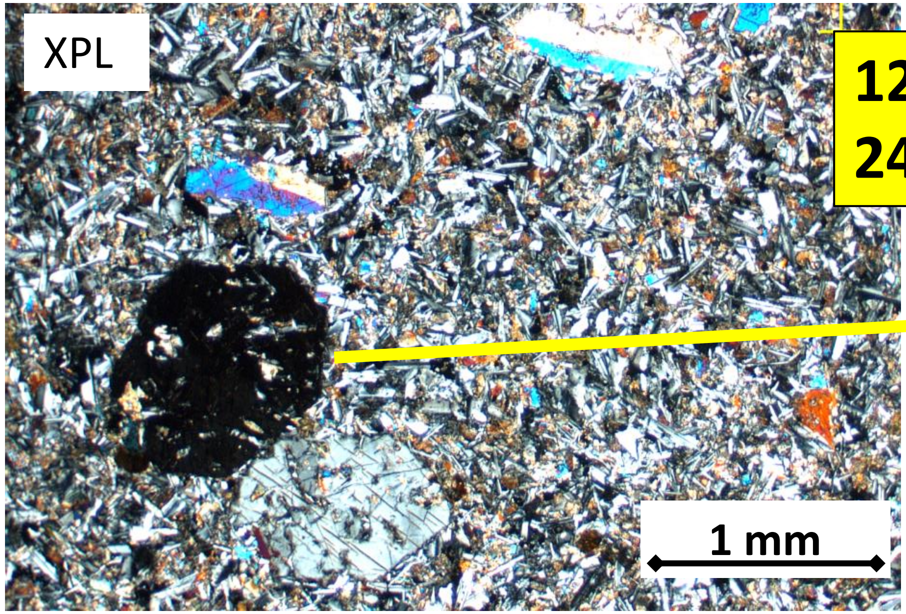
Crystal shapes, textures

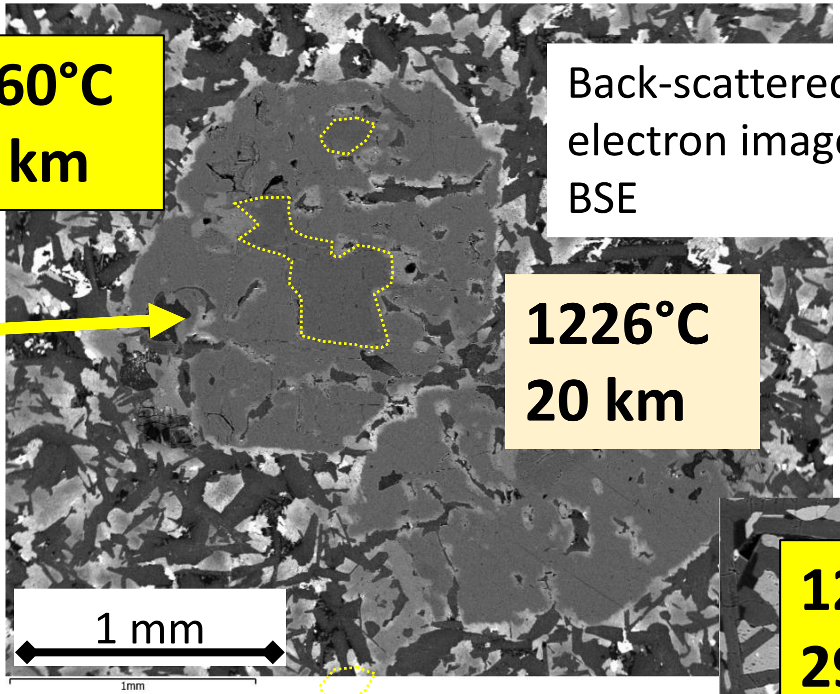
OPX cores – inside yellow dotted lines

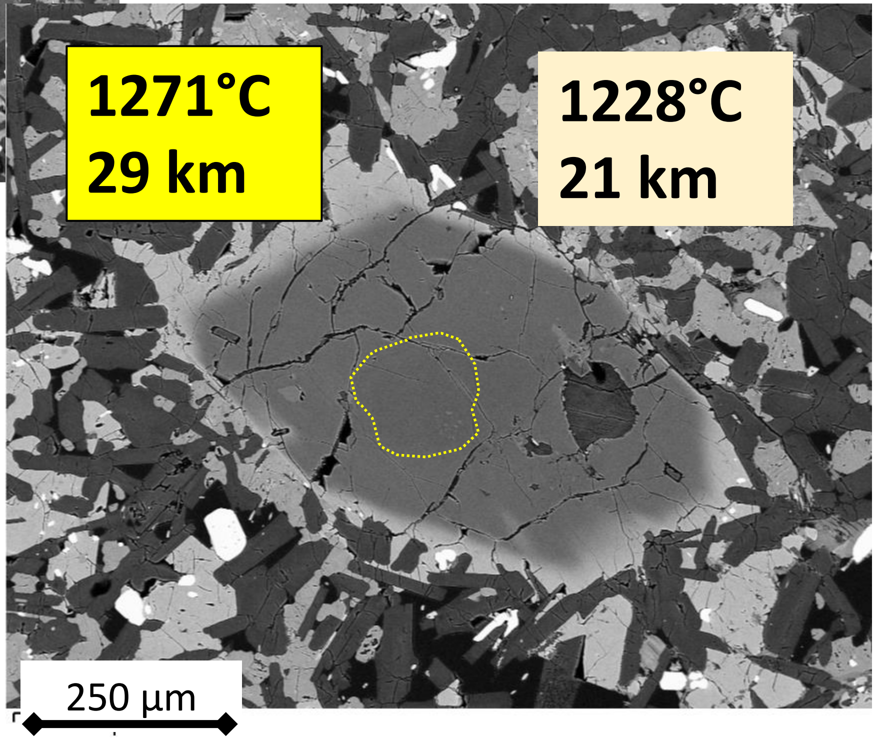
- more Mg-rich composition
- anhedral outline (not good crystal faces)
- found inside crystals of OPX (shown here) and AUG



CAMP Plumbing System: Evidence from Crystal Shapes, Textures







Temperature and depth values

OPX cores in yellow

OPX host crystals in light brown

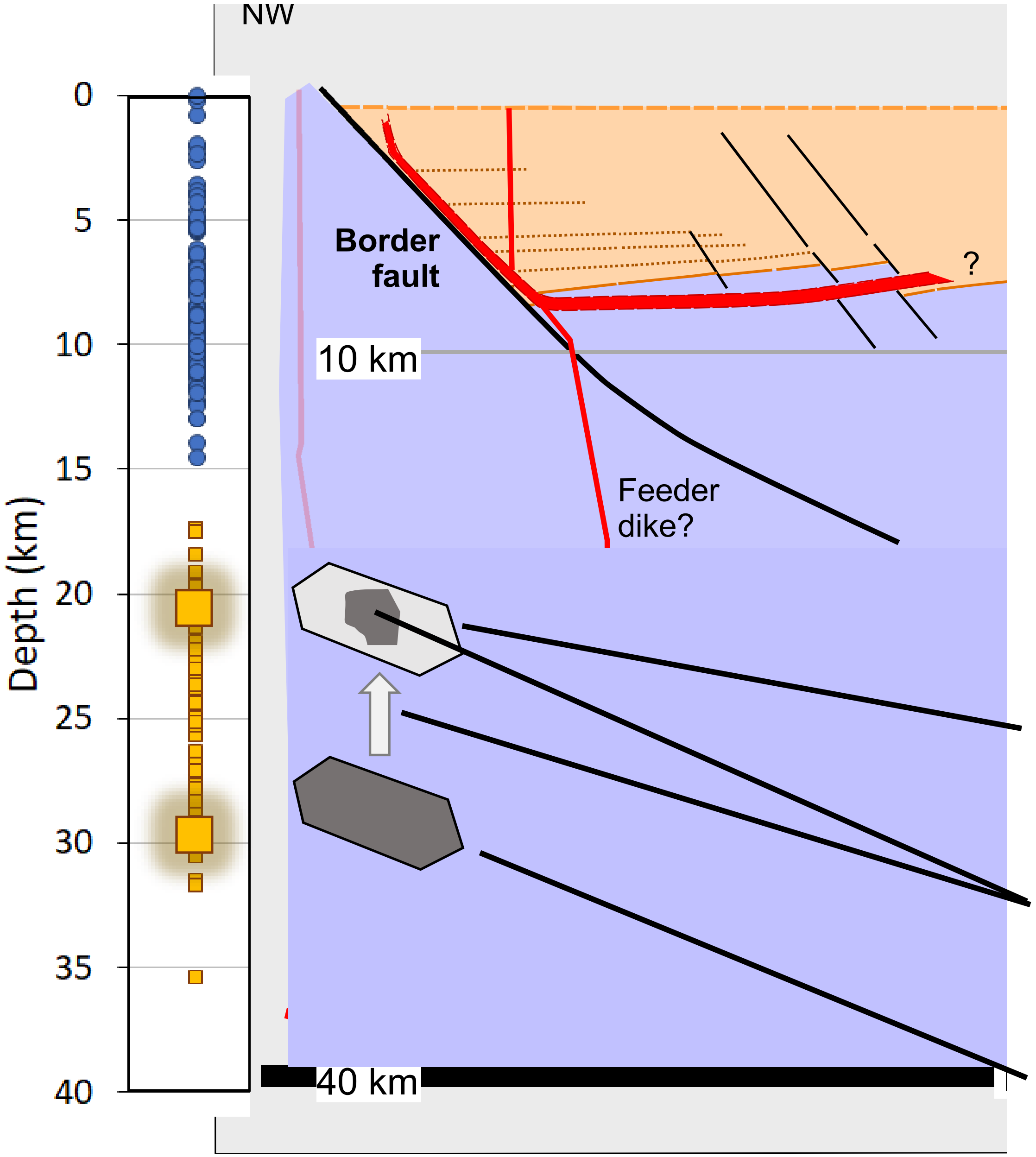
Crystal shapes, textures

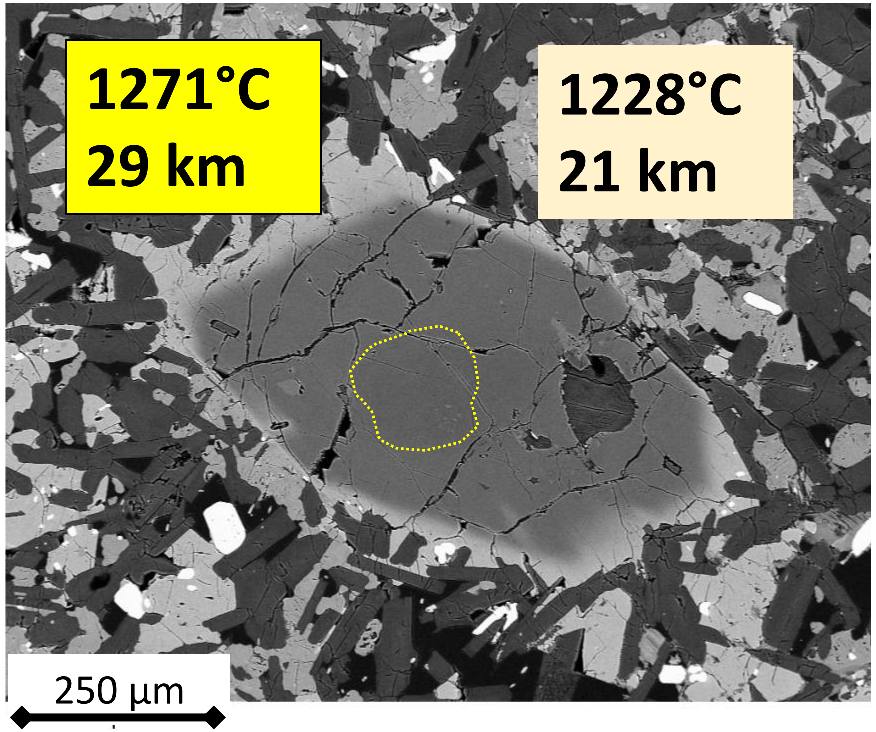
OPX cores – higher temperature and pressure (deeper)

Host OPX or AUG – lower T and P (not as deep)

How do we connect these data to the plumbing system?

CAMP Plumbing System: History of an OPX Crystal



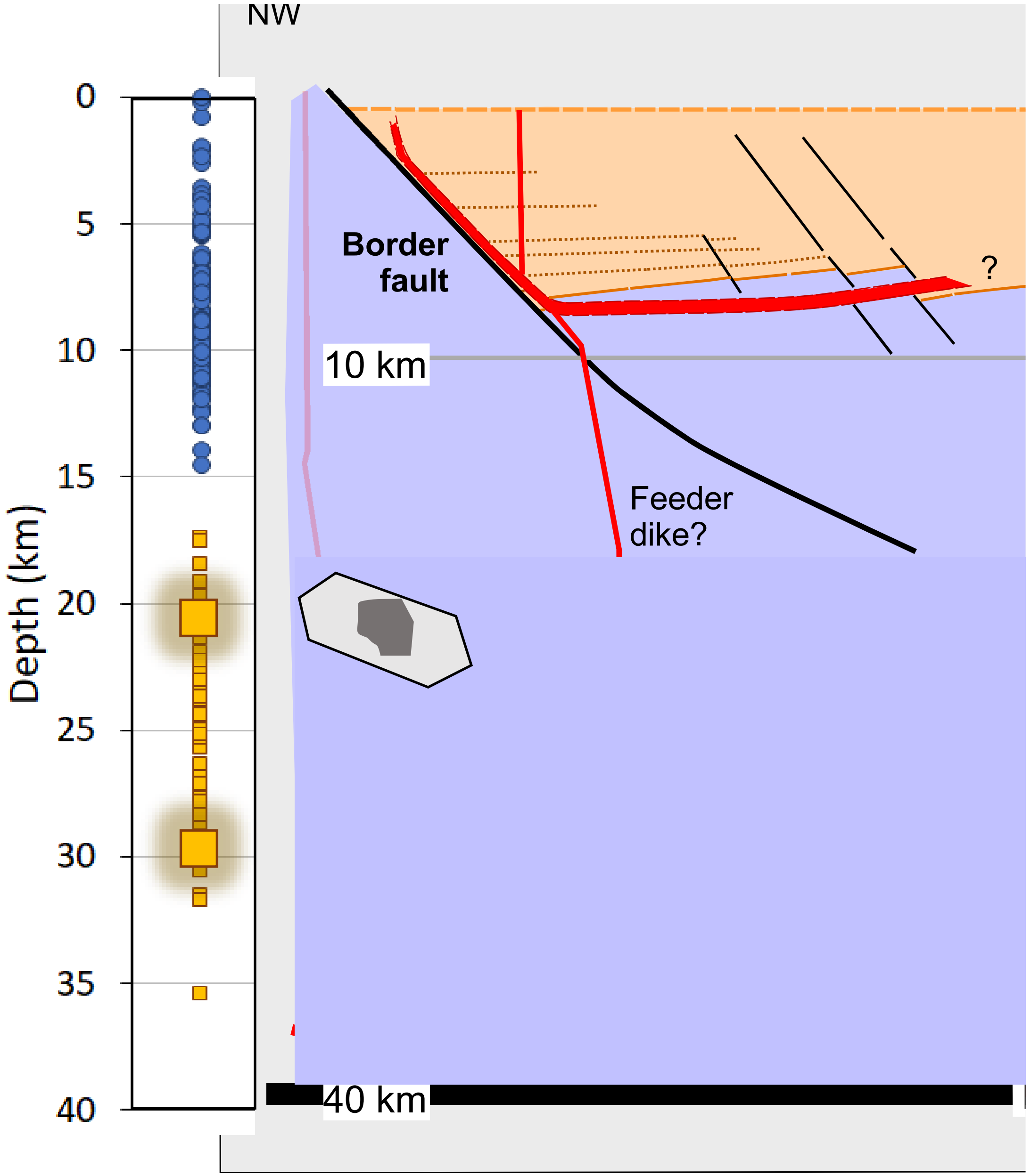


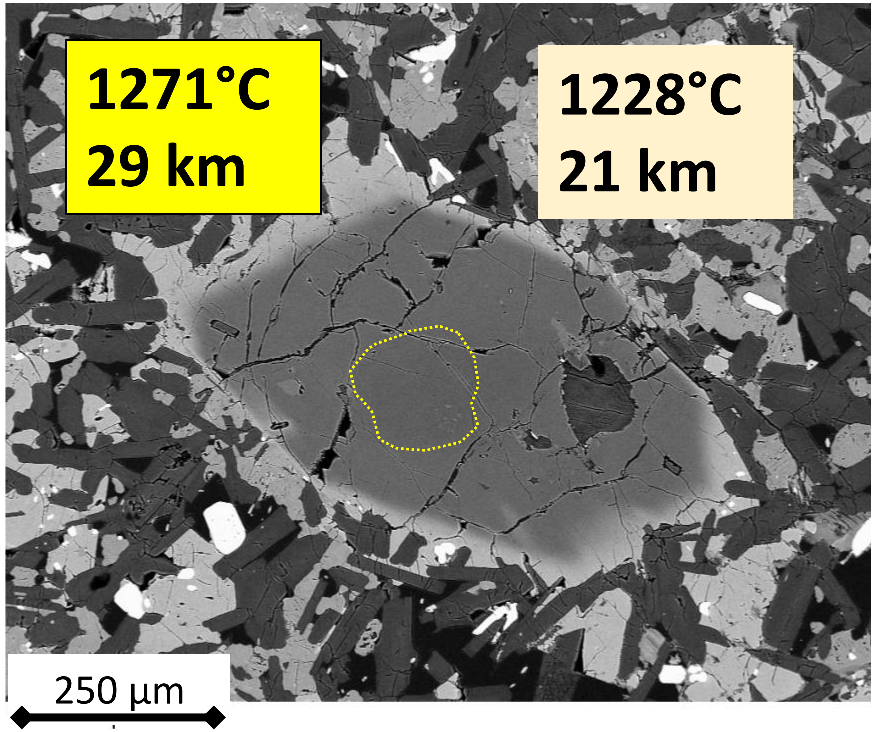
Crystal was nucleus for new growth at ~ 21 km

Crystal carried up by new magma, partly resorbed

Mg-rich OPX crystal grew at ~ 29 km

CAMP Plumbing System: Evidence from an OPX crystal





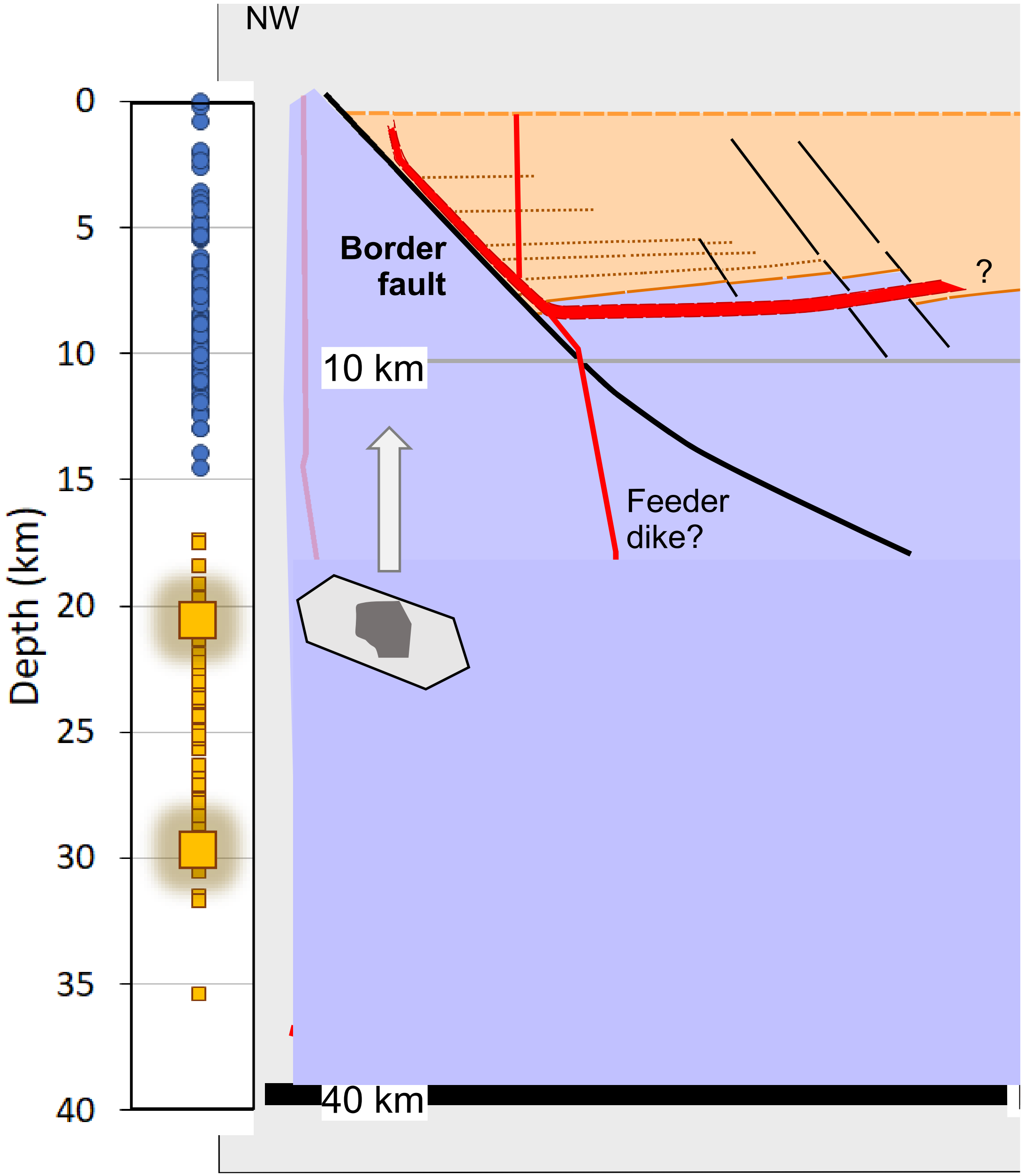
OPX crystal has a euhedral outline (crystal faces):

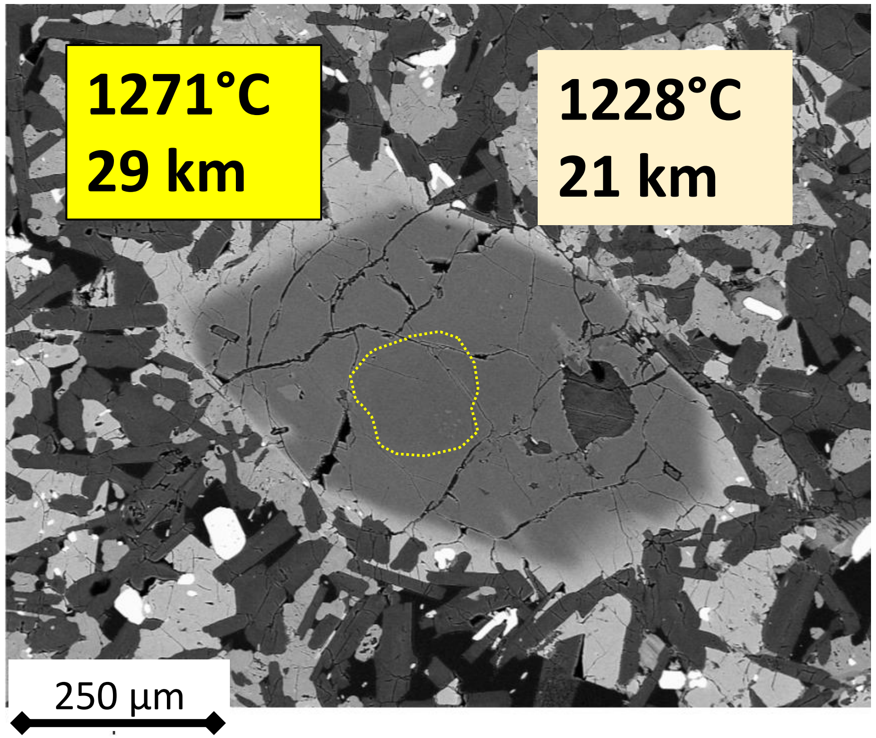
Crystal grew in liquid-rich environment

This would be consistent with growth while suspended in dike with convecting liquid

(see Holness et al., 2019)

CAMP Plumbing System: Evidence from an OPX crystal





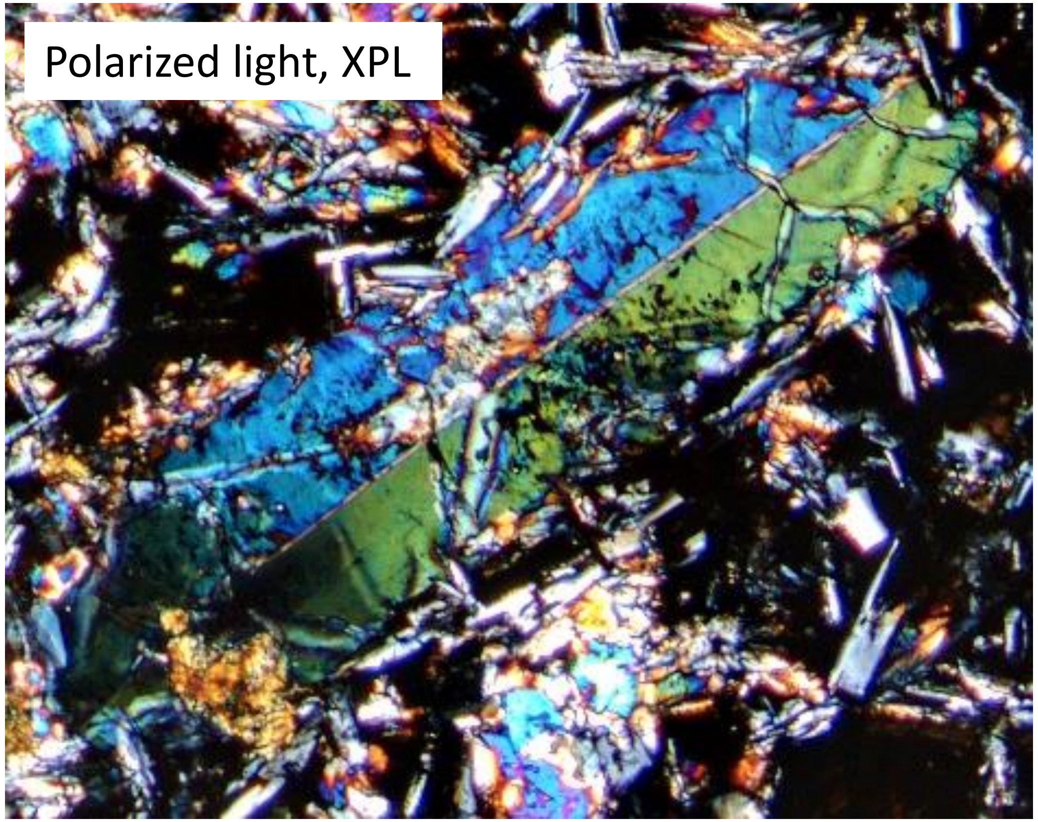
OPX Crystal has a thin rim (lighter gray, more Fe-rich), only slight resorption along core edge

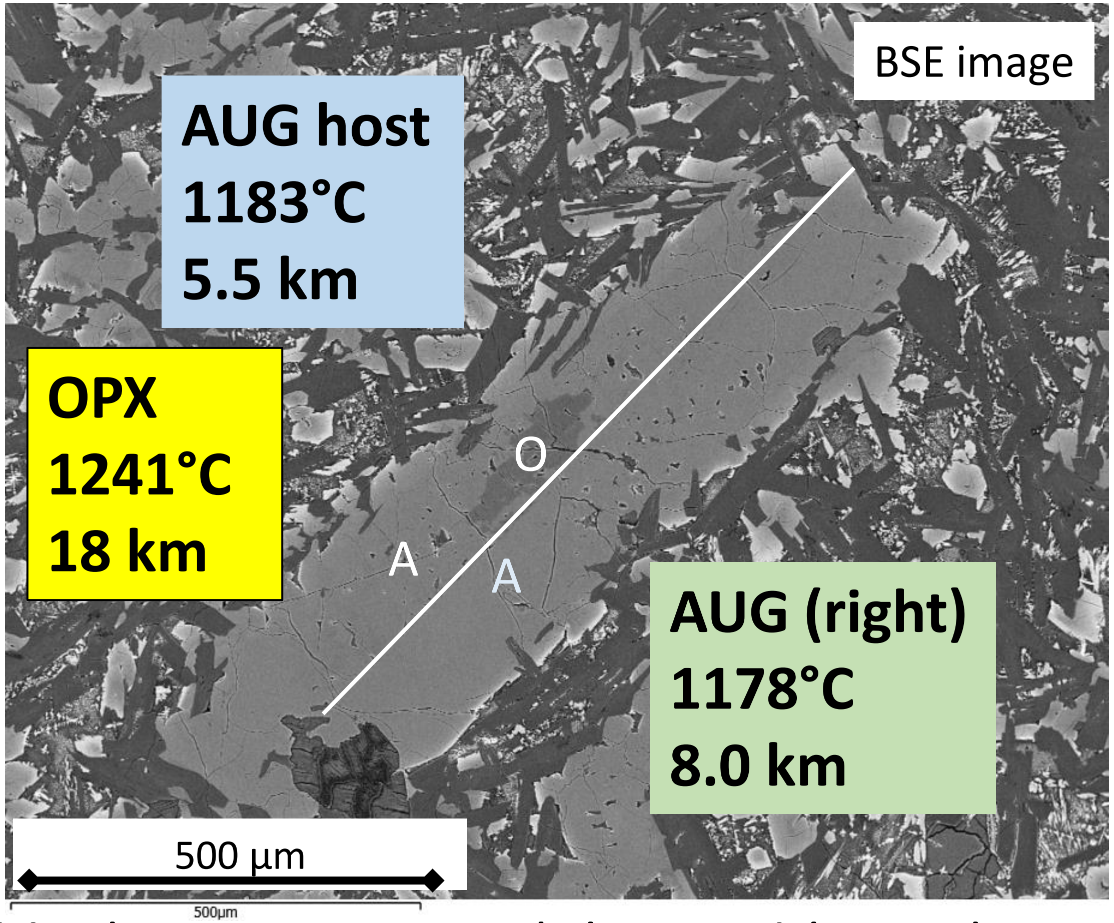
Crystal had rapid ascent from 21 km → 3.5 km in order to preserve crystal faces

Diffusion was relatively limited – this can be quantified by diffusion modeling

CAMP Plumbing System: History of a Small Crystal Aggregate

Crystals aggregated during transport in plumbing system





Three crystals in this aggregate:

OPX (O) core inside AUG (A) host crystal (blue); separate AUG (A) crystal (green)

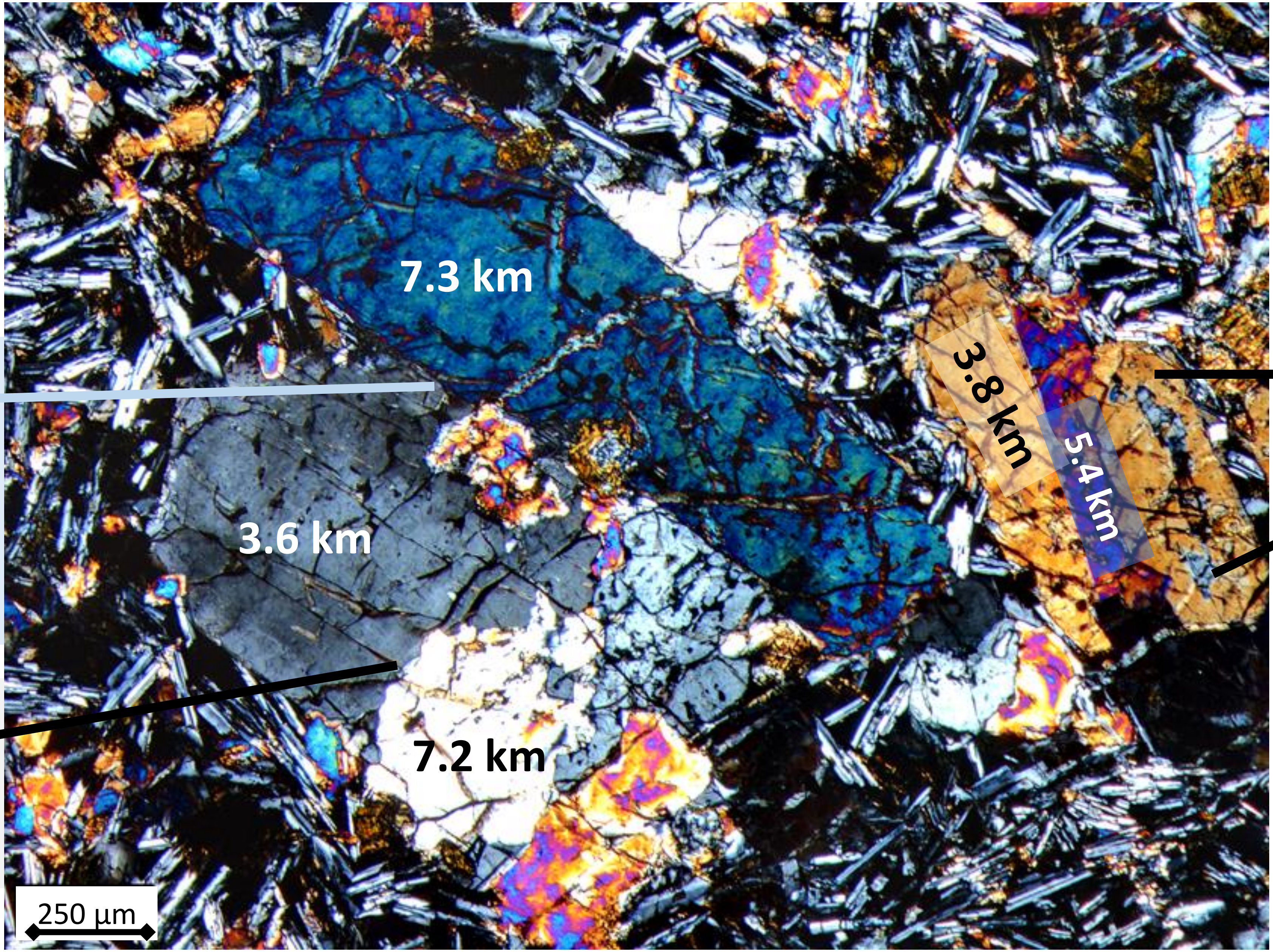
The 2 AUG crystals grew at different depths (pressures) and were attached along a planar crystal face during transport – a common igneous texture (***synneusis***)

Crystals aggregated during transport in plumbing system

Crystals grew at different depths (km), with different histories

straight grain boundaries – attachment after growth by synneusis, aggregation

undulose extinction irregular boundary – deformation in crystal mush?



Aggregated at or above 3.6 or 2.3 km

AUG host 2.3 km

OPX inclusion in AUG 23 km

Conclusions:

CAMP plumbing system and magma transport between source and rift basins

Evidence from petrology:

- ***Multiple batches of similar basalt magmas in plumbing system***
- ***Rapid transport of magma from lower/middle crust (20-25 km depth) up to rift basin***
- ***Crystals grew in liquid-rich environment*** (possibly suspended in convecting liquid in dike)
- ***Crystals aggregated during transport***

Evidence above suggests dikes were important for crystal growth and transport in plumbing system

Sills were also important component of plumbing system

There are other characteristics of early-formed crystals and clusters not discussed in this talk

Outline of presentation

- CAMP plumbing system in the rift basin –
  previous talk by Martha Withjack
- Magma transport and flow within the rift-basin plumbing system
- CAMP plumbing system in the crust between the magma source region (upper mantle) and the rift basin (~ 8 to 40 km)
- Magma transport and flow in the trans-crustal plumbing system
  - **Petrologic evidence**
  - **Field evidence (existing geologic maps, Smith et al., 1975)**
  - **Seismic evidence (other studies in literature)**
  - **Geochemical evidence (other studies in literature)**

CAMP Plumbing System: Evidence from Field Studies
Triassic-Jurassic rift basins and intrusions, SE Pennsylvania
(red dikes are from 1st phase of CAMP only)

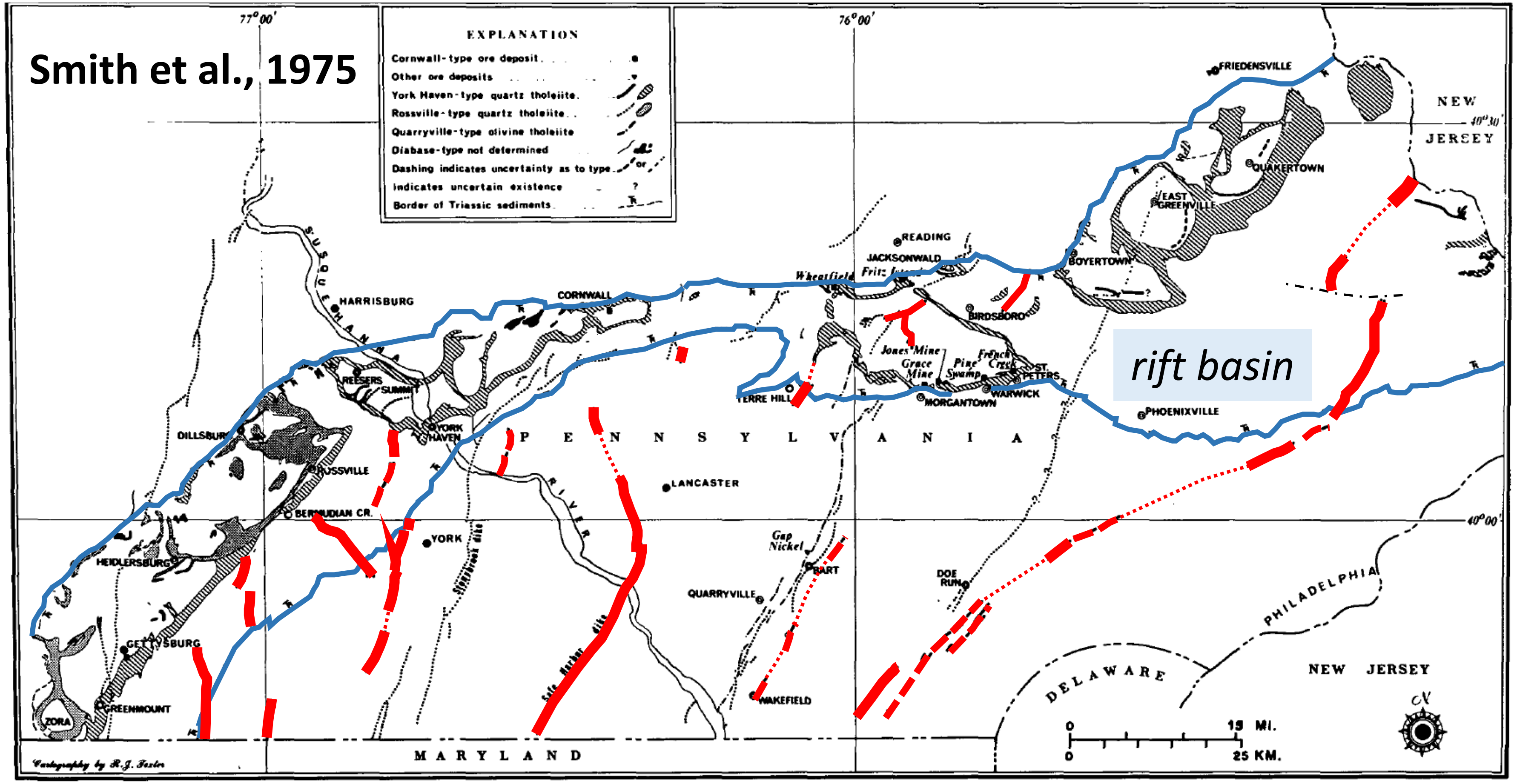


Figure 1. Distribution of three types of diabase in Pennsylvania. Map based on field observations and chemical analyses by R. C. Smith II and R. M. Lanning, state geological map (Gray and others, 1960), Longwill and Wood (1965), Peter W. Weigand (1970, personal commun.), D. B. MacLachlan (1973, personal commun.), and other sources.

Blue outline – boundaries of Mesozoic rift basin

South of rift basin is Precambrian and Paleozoic basement beneath rift basin

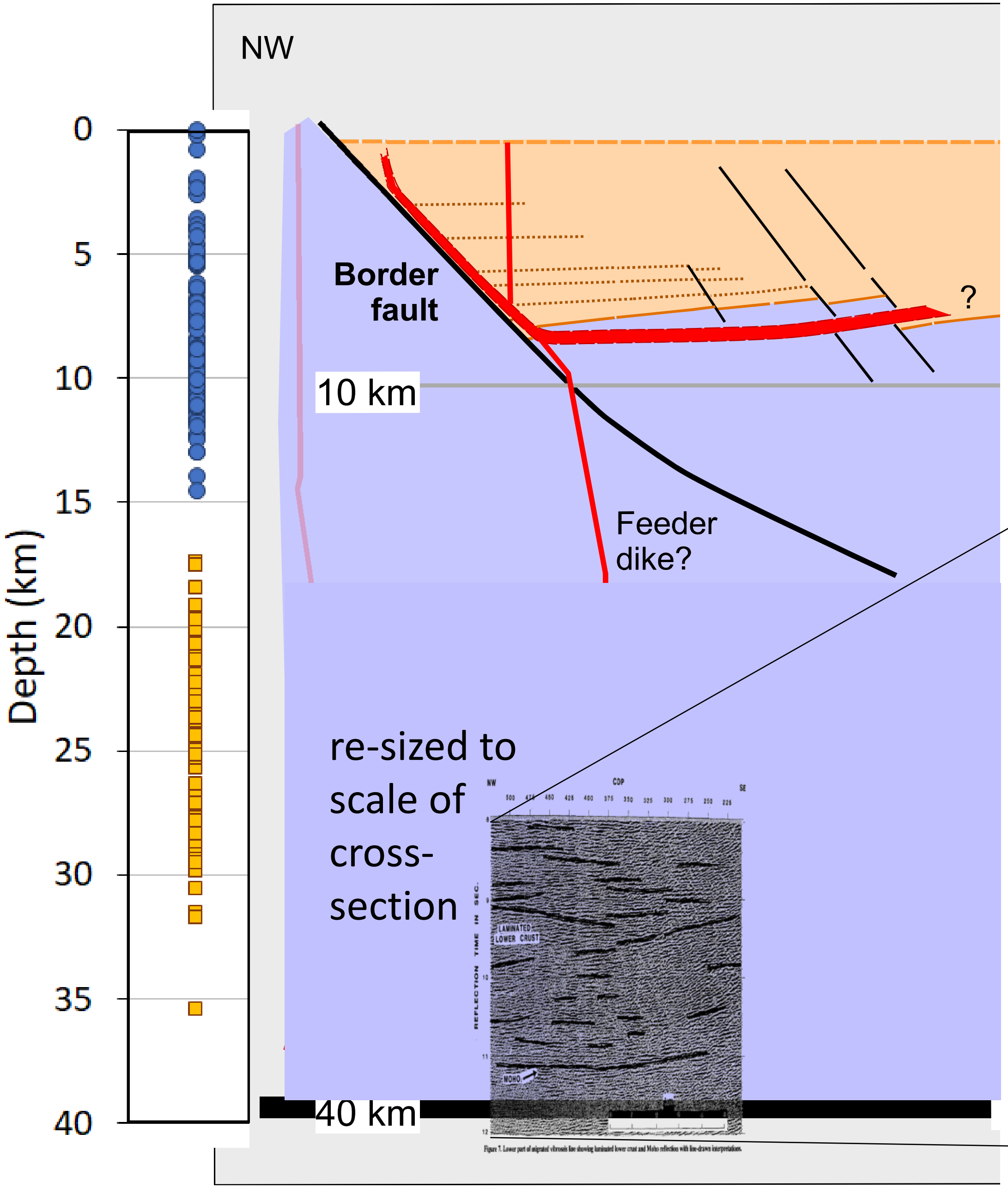
~ 8 – 11 km depth at CAMP time (~201 Ma)

All CAMP intrusions in basement under rift basins are DIKES, not sills

CAMP Plumbing System: Evidence from Seismic Studies

Sheridan et al., 1991 – seismic reflection beneath Buena basin, NJ (buried basin)

Laminated lower crust: CAMP mafic sills?



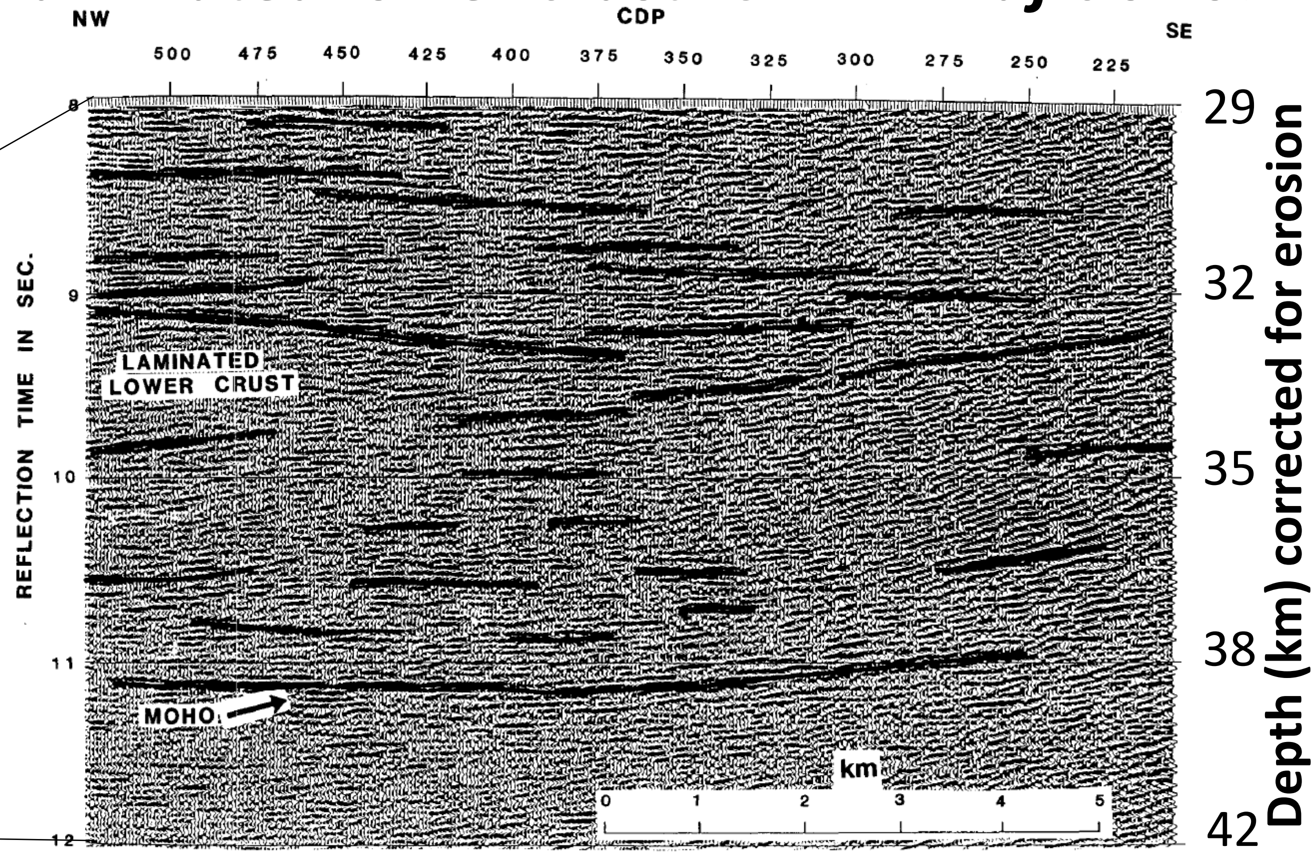
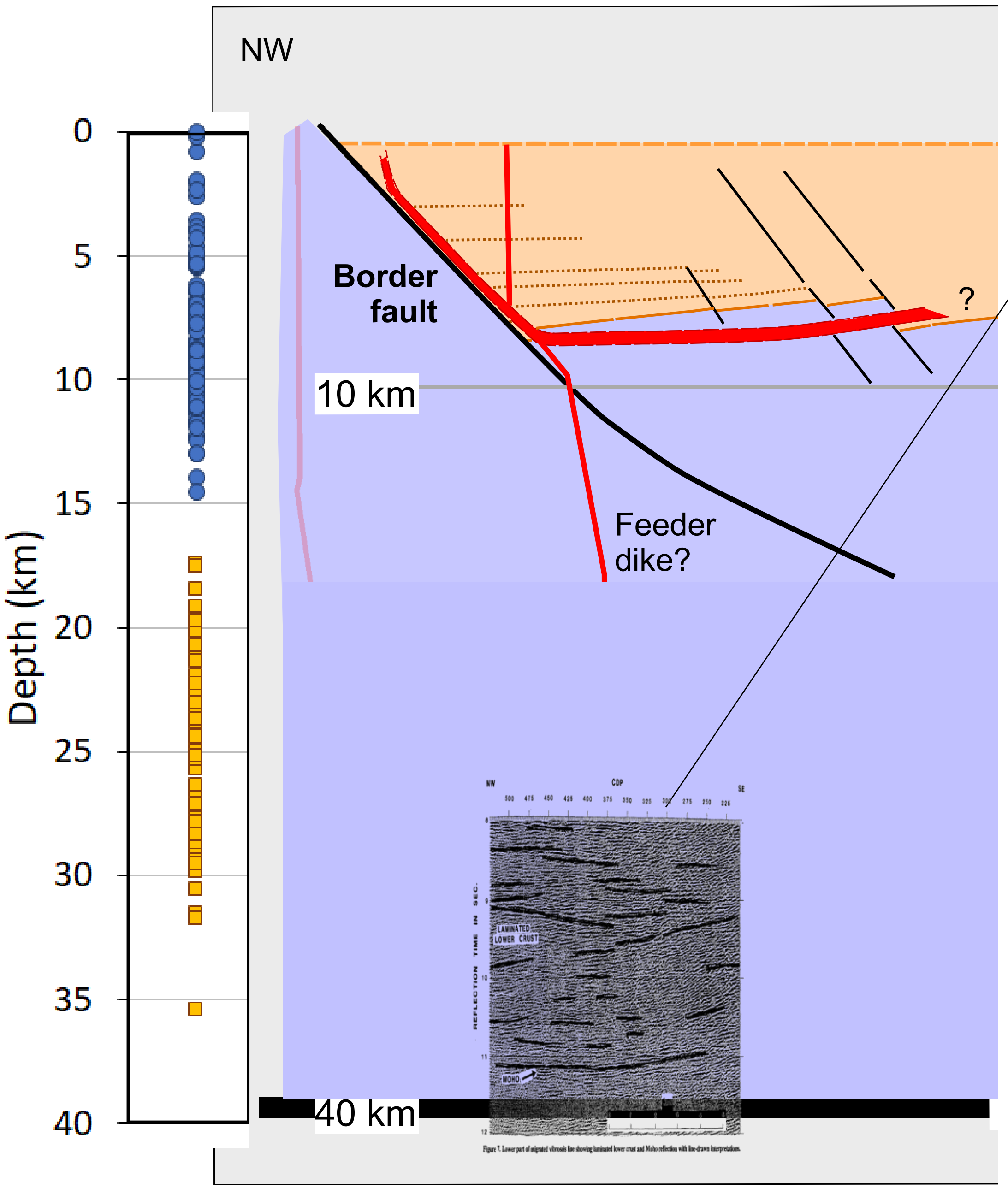


Figure 7. Lower part of migrated vibroseis line showing laminated lower crust and Moho reflection with line-drawn interpretations.



CAMP Plumbing System: Evidence from Seismic Studies

Laminated lower crust: CAMP mafic sills?

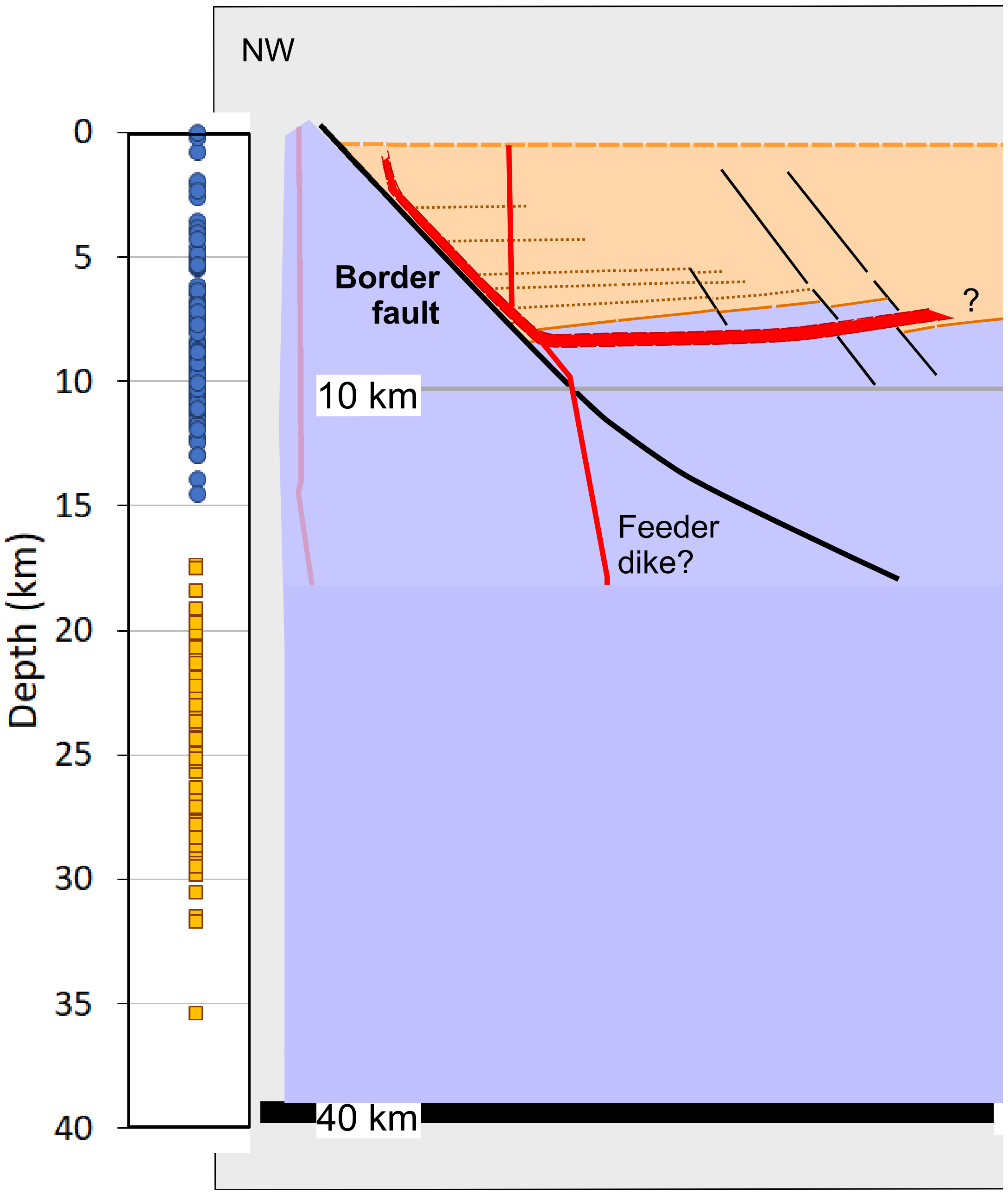
- Sheridan et al., 1991 – Buena basin, NJ
- Hutchinson et al., 1986 – Long Island platform, buried basins

High seismic velocity in lower crust (dense, mafic lower crust)

- Gao et al., 2020 – Hartford basin, CT
- Marzen et al., 2020 – S Georgia basin

Velocity not elevated in middle crust

- Lizarralde et al., 1997, and the above



CAMP Plumbing System: Evidence from Geochemistry

Geochemical and isotopic studies of CAMP magmas

- *crust recycling in mantle source*
- *limited assimilation*
- ***interaction with materials from the lower crust and/or upper crust– not middle crust***

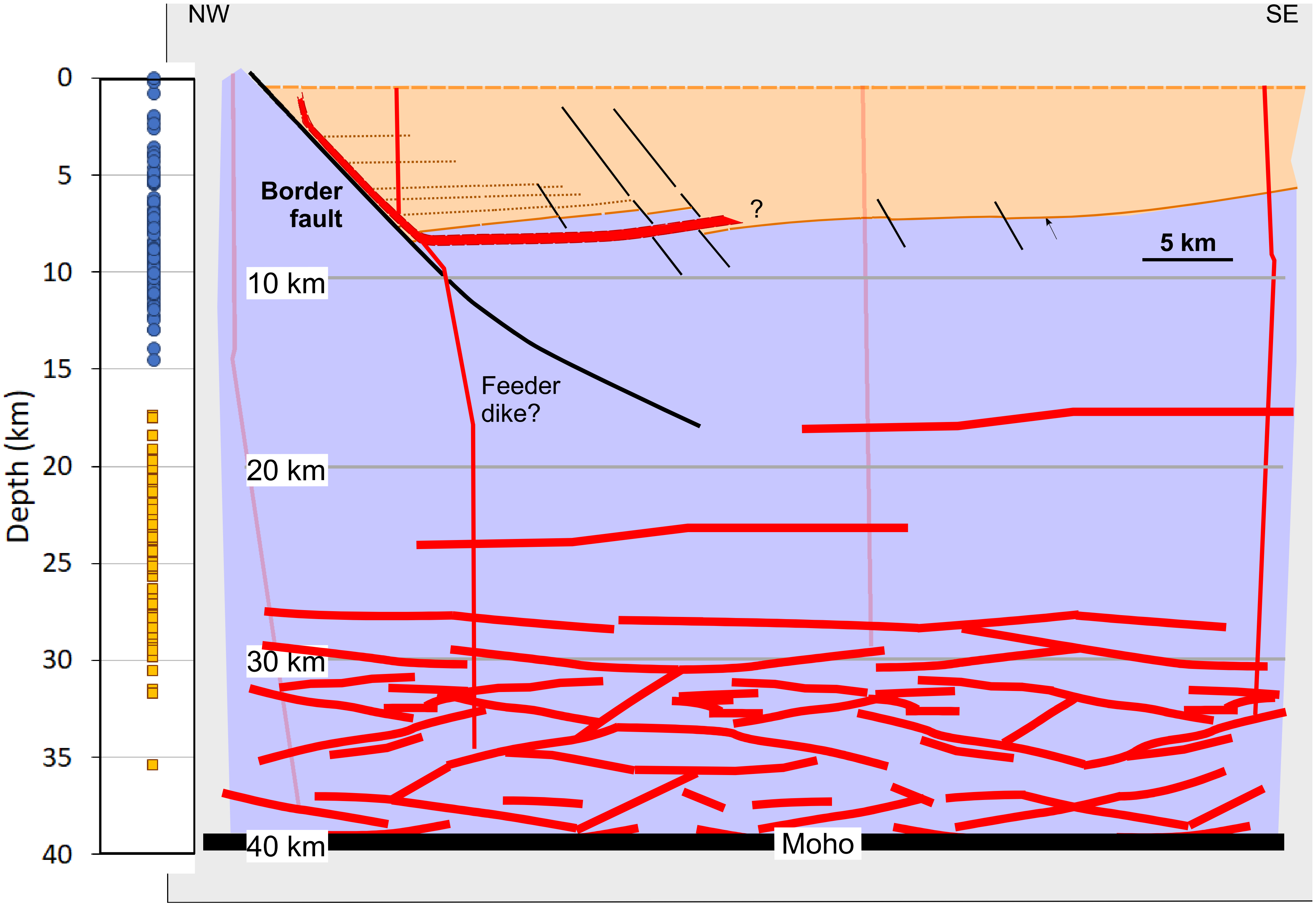
Callegaro et al., 2013

Merle et al., 2013

Whalen et al., 2015

and earlier studies

CAMP Plumbing System: A Possible Model

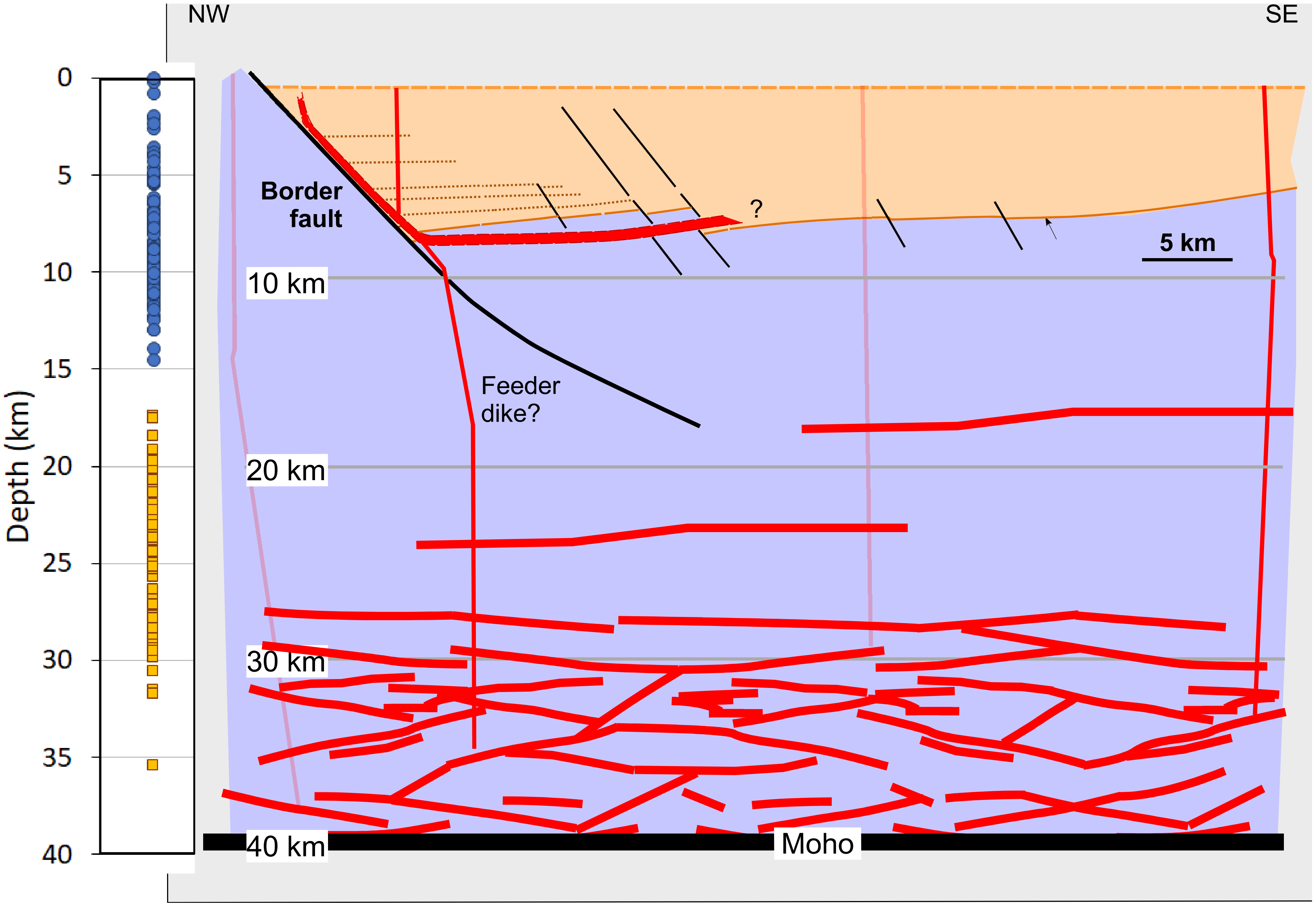


Dike-sill complexes in rift basin, 0-8 km

Dikes possibly the major intrusion type in middle crust 8 – 25 km

Consistent with geologic maps that show only dikes in basement below rift basins (~ 8 – 11 km)

CAMP Plumbing System: A Possible Model

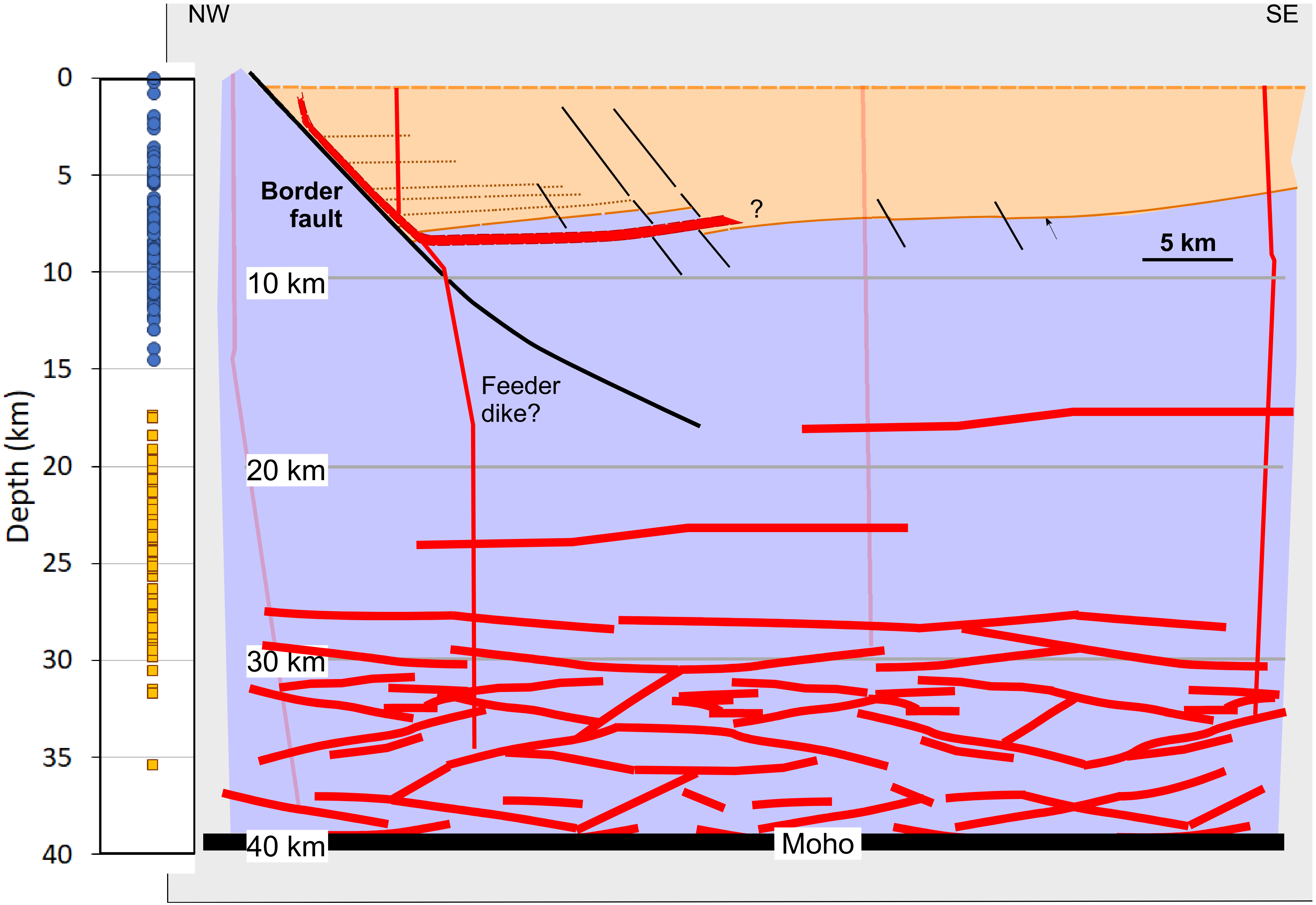


Dikes possibly the major intrusion type in middle crust 8 – 25 km

Consistent with lack of high seismic velocities in middle crust

Consistent with models that show lack of middle-crust geochemical and isotopic signatures in CAMP basalts

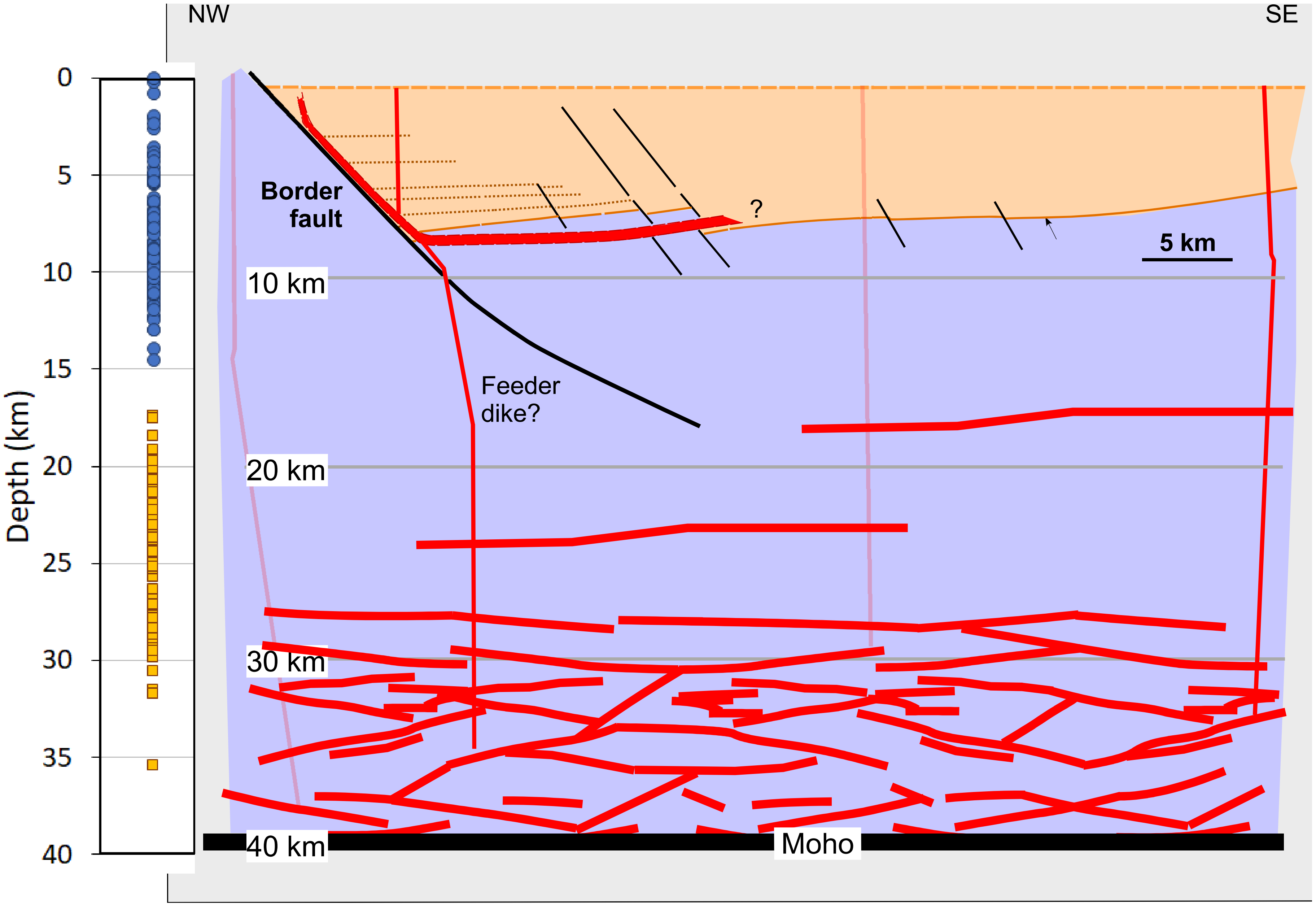
CAMP Plumbing System: A Possible Model



Dike-sill complexes in lower crust, 25-40 km

Consistent with seismic studies that indicate multiple reflectors and high velocities in lower crust at ~ 25-40 km beneath rift basins of Eastern North American margin

CAMP Plumbing System: A Possible Model



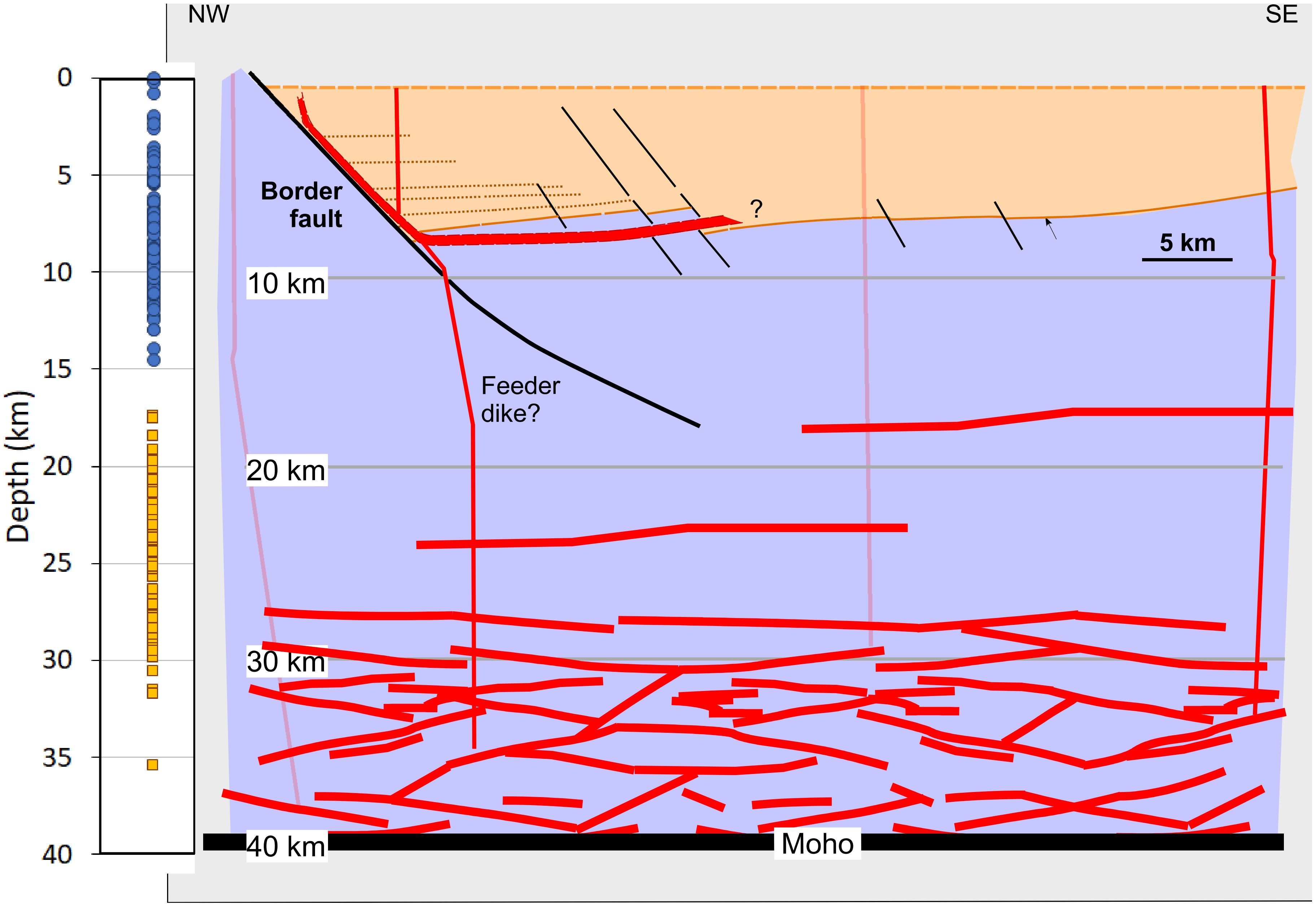
Dike-sill complexes in rift basin, 0-8 km

Dikes possibly the major intrusion type in middle crust 8 – 25 km

Dike-sill complexes in lower crust, 25-40 km

SO WHAT?

CAMP Plumbing System: Enabled Rapid Transport



Dike segments in rift basin result in → efficient, rapid transport in upper crust to eruption

Dikes in middle crust result in → efficient, rapid transport of basaltic magmas from lower crust into rift basin

Conclusions

What was the CAMP plumbing system like, in rift basins and between source and basin?

- **Reconstruction of tilted, eroded Morgantown intrusion reveals a complex shape including sub-horizontal sill segments and steeply-dipping sheet/ramp/dike segments**
- **Magma flowed along pre-existing zones of structural weakness to build the Morgantown intrusion**
- **Evidence from pyroxene-melt thermobarometry, field mapping, seismic studies, and geochemistry is consistent with sill-dike complexes in the rift basin (0 – 8 km) and middle/lower crust (25 – 40 km) and mostly dikes in middle/upper crust (8 – 25 km)**

How did magma transport in the plumbing system influence magma flux and eruption?

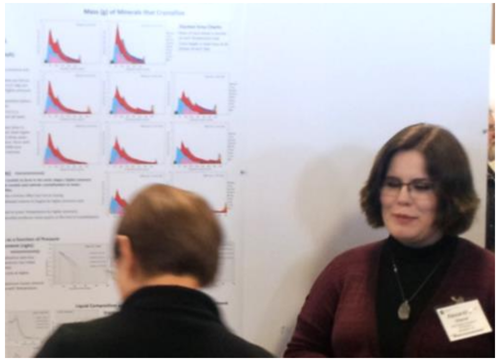
- **Dikes in middle/upper crust (8 – 25 km) enabled rapid transport of initial magmas from mantle and sill complexes at depth up into rift basin**
- **Lateral flows distributed crystal cargo in deep sill segments; vertical flows along Border and Birdsboro faults enabled rapid transport of initial magmas to eruption sites on surface, and the continued upward transport of evolved magmas and fluids promoting venting of magmatic gases**
- **Rapid transport by dikes and steeply-dipping intrusion segments contributed to the eruption of a large volume of basalt in a geologically short time during the first phase of CAMP magmatism (~ 201.5 Ma)**

Acknowledgements

This research was conducted on land that is part of the traditional territory of the Lenni-Lenape, called “Lenapehoking,” probably the dialect clan of the Munsee, “People of the Stony Country,” in the headwaters region of the Delaware River. LeeAnn acknowledges the Lenni-Lenape as the original people of this land and their continuing relationship with their territory.
(modified from the Land Acknowledgement,
Nanticoke-Lenni-Lenape Tribal Nation, https:\\nlltribe.com)

LeeAnn thanks: her co-authors and colleague Dr. MaryAnn Malinconico; many generations of students, in Petrology classes and research assistants (pictured) at Dept. Earth-Space Sciences, WCU, especially: ***Alison Aungst, Joseph Budnovitch, Steve Esrey*** (not pictured) who helped analyze the pyroxenes in this study

Funding from WCU and PASSHE



References cited:

Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., McHone, G., Rasbury, E.T., and Et-Touhami, M., 2013, Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province: Science, v. 340, p. 941-945.

Callegaro, S., Marzoli, A., Bertrand, H., Chiaradia, M., Reisberg, L., Meyzen, C., Bellieni, G., Weems, R.E., and Merle, R, 2013, Upper and lower crust recycling in the source of CAMP basaltic dykes from southeastern North America: Earth and Planetary Science Letters, v. 376, p. 186-199, DOI: 10.1016/j.epsl.2013.06.023

Capriolo, M., Marzoli, A., Aradi, L. E., Callegaro, S., Dal Corso, J., Newton, R. J., Mills, B. J.W., Wignall, P. B., Bartoli, O., Baker, D.R., Youbi, N., Remusat, L., Spiess, R., and Szabó, C., 2020, Deep CO2 in the end-Triassic Central Atlantic Magmatic Province: Nature Communications, v. 11, Issue 1, DOI: 10.1038/s41467-020-15325-6.

Froelich, A.J., and Gottfried, D., 1985, Early Jurassic diabase sheets of the eastern United States – a preliminary overview: in, Robinson, G.R., and Froelich, A.J., eds., Proceedings of the Second U.S. Geological Survey Workshop on the Early Mesozoic Basins of the Eastern United States: U.S. Geological Survey Circular 946, p. 79-86.

Froelich, A.J., and Gottfried, D., 1999, Chapter 12B: Early Mesozoic – Igneous and contact metamorphic rocks: in, Schultz, Charles H., ed., The Geology of Pennsylvania, Harrisburg, PA: Pennsylvania Geological Survey Special Publication no. 1, p. 203-209.

Gao, H. Y., Yang, X. T., Long, M. D., and Aragon, J. C., 2020, Seismic Evidence for Crustal Modification Beneath the Hartford Rift Basin in the Northeastern United States: Geophysical Research Letters, v. 47 Issue 17, DOI: 10.1029/2020gl089316.

Holness, M. B., Neufeld, J. A., Gilbert, A. J., and Macdonald, R., 2017, Orientation of tabular mafic intrusions controls convective vigour and crystallization style: Journal of Petrology, v. 58, Issue 10, p. 2035-2053, DOI: 10.1093/petrology/egx081.

Holness, M. B., Stock, M. J., and Geist, D., 2019, Magma chambers versus mush zones: constraining the architecture of sub-volcanic plumbing systems from microstructural analysis of crystalline enclaves: Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, v. 377, Issue 2139, DOI: 10.1098/rsta.2018.0006.

Husch, J.M., 1992, Geochemistry and petrogenesis of Early Jurassic diabase from the central Newark Basin of New Jersey and Pennsylvania: in, Puffer, J.H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 169-191.

Hutchinson, D. R., Klitgord, K. D., and Detrick, R. S., 1986, Rift basins of the Long Island Platform: Geological Society of America Bulletin, v. 97, Issue 6, p. 688-702, DOI: 10.1130/0016-7606.

Lizarralde, D., and Holbrook, W. S., 1997, U.S. mid-Atlantic margin structure and early thermal evolution, Journal of Geophysical Research-Solid Earth, v. 102, Issue B10, p. 22855-22875, DOI: 10.1029/96jb03805.

Magee, C., Muirhead, J., Sch ofield, N., Walker, R. J., Galland, O., Holford, S., Spacapan, J., Jackson, C. A-L., and McCarthy, W., 2019, Structural signatures of igneous sheet intrusion propagation: Journal of Structural Geology, v. 125, p. 148-154, DOI: 10.1016/j.jsg.2018.07.010.

Magee, C., Muirhead, J.D., Karvelas, A., Holford, S.P., Jackson, C.A.L., Bastow, I.D., Schofield, N., Stevenson, C.T.E., McLean, C., McCarthy, W., and Shtukert, O., 2016, Lateral magma flow in mafic sill complexes: Geosphere, v. 12, p. 809-841.

Mangan, M.T., Marsh, B.D., Froelich, A.J., and Gottfried, D., 1993, Emplacement and differentiation of the York Haven Diabase Sheet, Pennsylvania: Journal of Petrology, v. 34, p. 1271-1302.

Marzen, R. E., Shillington, D. J., Lizarralde, D., Knapp, J. H., Heffner, D. M., Davis, J. K., and Harder, S. H., 2020, Limited and localized magmatism in the Central Atlantic Magmatic Province: Nature Communications, v. 11, Issue 1, DOI: 10.1038/s41467-020-17193-6.

Merle, R., Marzoli, A., Reisberg, L., Bértrand, H., Nemchin, A., Chiaradia, M., Callegaro, S., Jourdan, F., Bellieni, G., Kontak, D., Puffer, J., and McHone, J.G., 2013, Sr, Nd, Pb, and Os isotope systematics of CAMP tholeiites from Eastern North America (ENA): evidence of a subduction-enriched mantle source: Journal of Petrology, v. 55, p. 133-180.

Neave, D. A., and Putirka, K. D., 2017, A new clinopyroxene-liquid barometer, and implications for magma storage pressures under Icelandic rift zones: American Mineralogist, v. 102, Issue 4, p. 777-794, DOI: 10.2138/am-2017-5968.

Olsen, P., Withjack, M.O., Schlische, R., and Pazzaglia, F., 2018, Temporal, tectonic, climatic, and environmental context of the Triassic-Jurassic rift system of Eastern North America: emerging concepts from the Newark rift basin: Annual Field Conference of Pennsylvania Geologists, v. 83, Pennsylvania Geological Survey, https://www.fcopg.org/download-guidebooks.

Putirka, K. D., 2008, Thermometers and barometers for volcanic systems, in: Minerals, Inclusions and Volcanic Processes, Putirka, K. D., and Tepley, F. J., eds., Reviews in Mineralogy and Geochemistry, v. 69, p. 61-120, DOI 10.2138/rmg.2008.69.3.

Sheridan, R. E., Olsson, R. K., and Miller, J. J., 1991, Seismic reflection and gravity study of proposed Taconic suture under the New Jersey Coastal Plain: implications for continental growth: Geological Society of America Bulletin, v. 103, Issue 3, p. 402-414, DOI: 10.1130/0016-7606.

Smith, R.C., II, 1973, Geochemistry of Triassic diabase from southeastern Pennsylvania, [Ph.D. thesis]: University Park, Pennsylvania State University, 262 p.

Smith, R.C., II, Rose, A.W., and Lanning, R.M., 1975, Geology and geochemistry of Triassic diabase in Pennsylvania: Geological Society of America Bulletin, v. 86, p. 943-955.

Whalen, L., Gazel, E., Vidito, C., Puffer, J., Bizimis, M., Henika, W., and Caddick, M.J., 2015, Supercontinental inheritance and its influence on supercontinental breakup: The Central Atlantic Magmatic Province and the breakup of Pangea: Geochemistry Geophysics Geosystems, v. 16, Issue 10, p. 3532-3554, DOI: 10.1002/2015gc005885.

Woodruff, L.G., Froelich, A.J., Belkin, H.E., and Gottfried, D., 1995, Evolution of tholeiitic diabase sheet systems in the eastern United States: examples from the Culpeper Basin, Virginia-Maryland, and the Gettysburg Basin, Pennsylvania: Journal of Volcanology and Geothermal Research, v. 64, p. 143-169.