Penrose Conference Report

Processes of Crustal Differentiation: Crust-Mantle Interactions, Melting, and Granite Migration Through the Crust

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The origin and evolution of the continental crust pose intriguing questions that are being addressed by current research, and ideas on how melt segregates and migrates through the crust recently have been discussed in the literature. New insight has been triggered primarily by new laboratory and field observations. Within this context, we organized a GSA Penrose Conference to examine processes that contribute to the evolution of the continental crust. We started with six specific questions: (1)What are the dynamics of partial melting in the lower crust, and what is the rheological response of the crust to partial melting and melt transfer? (2) What is the role of crust-mantle interaction, and what geochemical signatures can be used to suggest additions of mass to the crust, crustal differentiation, and losses of mass from the crust during active deformation? (3) What are the specific links between the petrologic and structural, and the kinematic and dynamic expressions of melt migration?(4) What are the sources of heat to drive these processes? (5) What do we really need to know to test models of melt segregation and transfer in the continental crust? (6) What can we learn from recent results of research in the Ivrea-Verbano zone?

The conference, "Processes of Crustal Differentiation: Crust-Mantle Interactions, Melting, and Granite Migration Through the Crust," was held in Verbania, Italy, July 4–11, 1998. It brought together 83 geologists, with backgrounds ranging from petrology to geochemistry, from structural geology to geophysics, and from rock mechanics to magma dynamics, to consider the growth, modification, and differentiation of the continental crust. Participants came from 16 countries; 10 participants were students. Verbania is close by the Ivrea-Verbano zone, which is widely held to represent a section through the lower continental crust, uplifted and tilted to a near-vertical attitude during the Alpine orogeny. The Ivrea-Verbano zone is important because it is the putative example of magmatic underplating as the driving force for granulite facies metamorphism and depletion of lower crustal rocks by removal of a granite melt.

Field Excursions

Half the conference was devoted to field examination of rocks within the Ivrea-Verbano zone (and Permian granites within the adjacent Serie dei Laghi). An overview of the main units and structures of the Ivrea-Verbano zone is possible in the Valle d'Ossola, immediately to the west of Verbania, because of the wide valley produced by the River Toce, which cuts across the strike of the zone. Conference participants took part in an excursion along the Valle d'Ossola with field trip leaders Ernie Rutter and Rolf Schmid. On other excursions, participants examined the mafic complex and its roof rocks in the Val Sesia, saw the granulite facies "stronalites" (depleted granulites) and amphibolite facies migmatites in the Val Strona di Omegna and visited one of the Permian granites in the Serie dei Laghi, studied the migmatites in the Val Strona di Postua above the thickest part of the mafic complex, and examined peridotites within the mafic complex, particularly the Balmuccia peridotite, the top of which was once thought to represent the Moho. Two trips featured the geology next to the Insubric Line and structures within the mafic complex, including septa of depleted lower crustal rocks. These specialist field trips were based on detailed research by the leaders, their collaborators, and students.

Oral and Poster Sessions

The conference began with a presentation by Bruce Hobbs concerning fluid transport in the lithosphere, with particular reference to the influence of deformation. The traditional approach of representing the constitutive behavior of the lithosphere as either viscous at high temperature or brittle at low temperature disregards important aspects of constitutive behavior such as elasticity, yield, deformation-induced dilatancy, and strain-rate dependency. These behaviors are important in any consideration of fluid transport in real rocks. During Darcy flow, which depends on the presence within the rock mass of an interconnected pore space, the constitutive behavior is elasto-plastic with deformation-induced dilatancy. Fluid transport is focused by deformation-induced changes in pore pressure and permeability and not by the rheology of the material. Bruce introduced the term "Connolly flow" for fluid transport in rock masses with low intrinsic interconnected porosity, which is more realistic in the middle and lower crust. Fluid flow occurs through the propagation of high-permeability packets, the permeability distribution being controlled by deformation-induced permeability increases and decreases. In Connolly flow, the transport may or may not be focused, but the overall control on fluid transport is the rheology and state of stress of the material rather than the initial porosity and permeability distribution. These two modes of fluid transport have important geological consequences, since under conditions of Darcy flow, fluid is expected to be focused into rocks of high intrinsic permeability, which commonly are strong, whereas under conditions of Connolly flow, fluid is expected to be focused into rocks of low strength, which commonly have low intrinsic permeability.

A keynote presentation by Jean-Pierre Burg concerned feedback relations among migmatites, large-scale tectonics, and detachments in collisional orogens. He suggested that mid-crustal migmatites produced decoupling of upper from lower crust, explaining why the Moho is not observed in collisional orogens such as the Himalayas. He argued that the lower and upper crust thicken separately and by different mechanisms, an interesting hypothesis that carries the implication that the crust must have been hot before thickening if there existed a layer of migmatites with sub-horizontal fabrics. Specific examples of feedback relations between deformation and melt transport were provided by Gary Solar (crustal modification by anatexis in obliquely convergent [transpressive] orogens) and Chris Wareham (crustal growth in arcs). Gary Solar suggested that the geometry of melt batches during escape from the anatectic zone was controlled by strain, on the basis of granites with different shapes that reflect the strain field in zones of flattening and zones of constriction within a crustal-scale shear zone system. Jamie Connolly considered the influence of rheology on compaction-driven fluid flow in oromanure storage basin for evidence of seepage and contamination. Students discussed the site geology, facility design, and water-quality samples with great enthusiasm—until the wind shifted.

These are just a very few of the many examples of the ingenuity and effectiveness of PEP volunteers in supporting formal and informal earth sciences education.

The volunteers, in turn, are supported by the commitment and generosity of the PEP Club—donors who share GSA's vision about the value of local person-to-person partnerships between geoscientist, teacher, and student. The donors' investment funds PEP's $100,000 annual budget for information materials, expense reimbursements, and program coordination.

GSA's goals for PEP are

- to double participation in the next five years—to have 20% of GSA's members serving as ambassadors for the geosciences;
- to enhance collaborative activities with the community youth groups such as Boy Scouts of America, Expanding Your Horizons, a university-based program supporting middle school girls to meet women in science, and Teach for America, encouraging teachers to go into rural and inner-city schools;
- to develop collaboration with other geoscience societies;
- to expand PEP to the broad geoscience community, so that other geoscientists and organizations can share in the benefit of partnering.

That we have such dreams is a credit to all the PEP partners—volunteers and donors—whose dedication has contributed to this wonderful program. ■

Digging Up the Past

Most memorable early geologic experience: "While carrying out a well inventory in Baldwin County, Alabama, young, budding hydrogeologist Philip LaMoreaux, attempting to knock on a back door, noticed the lady of the house taking a shower on the back porch. He retreated modestly."

—*Philip E. LaMoreaux*

1999 John C. Frye Environmental Geology Award

In cooperation with the Association of American State Geologists (AASG), GSA makes an annual award for the best paper on environmental geology published either by GSA or by one of the state geological surveys. The award is a $1000 cash prize from the endowment income of the GSA Foundation's John C. Frye Memorial Fund.

Criteria for Nomination

Nominations can be made by anyone, on the basis of the following criteria:
(1) paper must be selected from GSA or state geological survey publications, (2) paper must be selected from those published during the preceding three full calendar years, (3) nomination must include a paragraph stating the pertinence of the paper, (4) **nominations must be sent to Executive Director, GSA, P.O. Box 9140, Boulder, CO 80301.** *Deadline: March 31, 1999.*

Basis for Selection

Each nominated paper will be judged on the uniqueness or significance as a model of its type of work and report and its overall worthiness for the award. In addition, nominated papers must establish an environmental problem or need, provide substantive information on the basic geology or geologic process pertinent to the problem, relate the geology to the problem or need, suggest solutions or provide appropriate land use recommendations based on the geology, present the information in a manner that is understandable and directly usable by geologists, and address the environmental need or resolve the problem. It is preferred that the paper be directly applicable by informed laypersons (e.g., planners, engineers).

1998 Award Recipient Named

The 1998 award was presented at the GSA Annual Meeting in Toronto, Canada, to David C. Noe, Candace L. Jochim, and William P. Rogers for their report, "A Guide to Swelling Soils for Colorado Homebuyers and Homeowners," Colorado Geological Survey Special Publication 43, 1997, 76 p.

New Director of Publications

Peggy S. Lehr

Electronic journals and speedier publication of journals and books are two of the challenges for GSA Publications Director Peg Lehr. Lehr, who began work at Boulder Headquarters in April, has 20 years of experience in publications, primarily in magazine and book publishing.

Lehr previously worked for 10 years at the Association of Operating Room Nurses in Denver, a nonprofit international nursing association with 48,000 members. There, as director of communications, she was responsible for editorial, advertising sales, public relations, production and art, circulation, marketing, and the mail and printing centers.

"I like association work because I like the commitment from the staff and volunteers—the staff tends to be service-oriented. I like the challenges of society publishing because they are diverse," Lehr said.

Lehr is enthusiastic about the changes at GSA.

"I am excited about working with a new membership and producing scholarly publications. I have always had an interest in education and GSA's publications are excellent examples of scholarly publication at its best," she said.

Lehr graduated from the University of Colorado, Boulder, with a B.S. in journalism and received an M.S. in communication from the University of Denver. Before working in the association industry, she worked in the editorial and production areas for several for-profit companies, in fields such as plastics, machinery, lifestyle magazines, and cable television marketing and engineering.

genic belts, and repeated the importance of including elasticity in rheological modeling; he pointed out that viscous models can fail. During dehydration reactions, the upward migration of the liberated metamorphic fluid is enabled by a solitary wave in porosity that occurs from an initial condition of no hydraulic connectivity at the reaction isograd. Mike Williams led a discussion focused on growth vs. modification of continental crust, a theme that would be central to discussions throughout the week. Bruce Hobbs attempted to explain how the porosity waves described by Jamie Connolly might be recorded in the geological record—possibly as a zone of veining, or as a shear zone or shear zone system, or as a fracture or set of fractures.

Mark Harrison addressed the petrologic and mechanical controls on episodic tectonics during continuous convergence, with particular reference to the India-Asia collision. He emphasized that if lithosphere history is an important control on orogenic processes, then young orogenic belts may not be good analogs for old orogens. Ed Sawyer considered closed-system crustal differentiation during large-scale anatexis. He emphasized the role of melt separation from residue during ascent, and how this process can cause late-stage modification of segregated melt by fractional crystallization. Jon Davidson addressed the issue of whether differences along strike in orogenic belts, such as the Andes, are controlled by source or by process. He emphasized the inevitability of crustal contamination, so that the important issue is how much contamination takes place in continental arcs, not whether it occurs. Furthermore, open-system differentiation is the rule rather than the exception in arcs, so that both additions to the crust and recycling of the crust occur. Fernando Bea used comparative geochemistry among Ivrea-Verbano zone granulites and Permian granites within the Serie dei Laghi, including Pb evaporation ages, to argue that the granites are older than the regional granulite-facies metamorphism and cannot be derived by closed-system melting of any known source. Thus, a simple link between depletion of the lower crust by loss of granitic melt during granulite-facies metamorphism, as previously postulated in this region, is brought into question. As an alternative, Bea postulated metasomatism of the lower crust due to fluid ingress from early mafic melts that underplated the crust. He suggested that melting of such a metasomatized fertile lower crust would yield granites consistent with the compositions of those in the Serie dei Laghi. The exposed lower crustal granulites are interpreted to reflect subsequent equilibration and cooling from granulite-facies conditions. Discussion was led by Mary Reid, who commented in particular on the need to have good data that address the absolute age of events and the distinction between growth and recycling of continental crust. Allen Glazner emphasized that mantle input to the crust is basaltic, which implies that a mafic-ultramafic component must lie below the Moho since the average crustal composition is broadly andesitic rather than basaltic. Thus, an important part of the crustal growth–crustal differentiation process concerns the mechanism by which this mafic or ultramafic material is returned below the Moho.

The poster session provided an opportunity for participants to present details of specific research on aspects of the crustal differentiation process. Thus, the content varied from what we can glean from particular minerals, whether a peritectic melting product in migmatites such as cordierite or the enigmatic rapakivi textures in which plagioclase forms a mantle around K-feldspar ovoids, to granulite facies metamorphism as viewed both from the field and the experimental capsule. Other posters presented results of research ranging from isotopic studies of rock suites and experimental melts, to geochronology, to microfabrics in migmatites and igneous rocks, and to the geochemistry of diatexites and ascent of granite.

The part of the program concerned with changes in crustal rheology with mineral reactions and triggers for active crustal growth began with a review of equilibrium melt distribution in partially molten systems. Although melt distribution at the grain scale is an important factor in controlling the segregation of granite melt from residue, low dihedral angles measured in all crustal analogs between melt and solid suggest that wetted grain boundaries are to be expected and interconnection of melt will be established at low volume % melt. Nonetheless, Didier Laporte argued that melt segregation may be inefficient at low volume % melting. He suggested there may be a range of melt fractions above the permeability threshold over which melt is interconnected but remains nearly stagnant. This raises the question of the role of deformation in the movement of granite melt at low volume % within a crustal source undergoing anatexis. The issue of deformation of partially molten synthetic granite was addressed by Julien Mecklenburgh, who described preliminary results of a laboratory study investigating granular flow of partially molten crustal analogs. Understanding the rheology and verifying flow laws of partially molten systems are important, and an interpretation of preliminary data suggests that at low melt fraction (~5–10 vol%), melt can be driven out of the source due to variations in deviatoric stress, whereas at moderate melt fraction (~20–30 vol%), the very low strength of the partially molten system allows en masse transfer by melt-assisted granular flow.

On a larger scale, preliminary results of three different approaches to modeling intrusive behavior were presented by Alison Ord. Many earlier treatments of this problem assumed nonelastic behavior for melts and a lack of yield behavior for crystal mushes or crystal-bearing magmas, both of which are unreasonable. For magmas with such behavior, a driving force for intrusion besides buoyancy is the shear stress induced by magma pressure differences or by deformation of the country rock. Alison Ord's models explored diapir structures, perhaps representative of magma intrusion in early Archean greenstone belts, and models to examine the effect of magma pressure on intrusion at high levels in the crust and the ascent of crystal-poor magmas by hydrofracture. The modeling theme was continued by Paul Bons, who described a model of deformation and melt accumulation by mobile melt fractures: movement of a package of melt with a fracture that is upward propagating ("hydro-fracture" propagation), but closing from behind. He suggested that melt segregations have to reach a critical size before the melt pocket can propagate upward as a crosscutting fracture. The chemical consequences of such a model depend on the rate of deformation; low rates of deformation lead to small variations in chemistry (equilibrium melting) and high rates of deformation leading to large variations in chemistry (fractional melting), because the former produce a batch of melt that reflects the integrated melting history, whereas the latter produce a batch of melt that preserves only a small part of the melting history. Alfons Berger and Jean Louis Vigneresse discussed the rheology of migmatites, partially molten systems, and partially crystallized systems, stressing that there are significant differences in behavior at any particular volume % liquid between partially molten and partially crystallized systems.

In starting the discussion, Ed Sawyer distinguished between melt-dominated and solid-dominated systems, and raised questions relating to the effect of the rate of melt production and the relationship to the rate of deformation. The question of what is represented by the leucosome in a migmatite was raised by Roger Powell. In his view, leucosomes are dominated by solid products of melting reactions and the melt itself is lost continuously or episodically from the reaction site. Migmatites are enigmatic, and whether they represent evidence of granite extraction from a source or failure of melt to escape from a source remains contentious, and both processes most likely occur in partially molten terranes. Several participants emphasized that leucocratic accumulations observed in relic anatectic systems may be produced by a combination of multiple processes. For example, migmatites may be produced by dehydration melting that leads to both a melt phase and peritectic solid products, and partial crystalliza-

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tion of the melt may lead to cumulate phases in the residue. In addition, melt may escape from the system, but an implication of such behavior is that melt may flow into the system to change again the composition of what ultimately becomes the leucosome.

The question of possible heat sources for crustal anatexis was addressed in a keynote lecture by Alan Thompson, who suggested that internal differentiation of the crust by anatexis is a localized phenomenon, that crustal evolution is dominated by the fractionation of hydrous mantle magmas in convergent arcs, and that remelting of lower crust in orogens must be common. These processes are driven either by crustal thickening, by invasion of mantle-derived magmas into the crust, or by lithospheric delamination and asthenospheric replacement. It was clear from this presentation and previous ones that melts derived from different sources within the crust-mantle system may coexist. Consequently, George Bergantz considered the constraints on communication between such melt batches. He focused on interfaces between batches and considered diffusive, convective, and chaotic regimes that lead to increased mixing efficiency. These results have considerable implications for magma mixing. John Foden addressed the issue of the changing composition of granite magmatism through time and its relationship to potential sources, given the decline in heat flow with increasing age of Earth. Foden emphasized that in the modern Earth, magmatism is concentrated at plate margins and catalyzed by water. He suggested that the proportion of crustal melting has decreased with the evolution of Earth, although evidence of mixing between mantle- and crust-derived magmas is common in continental arcs. Sue Debari emphasized that tonalite plutons in the North Cascades crystalline core are mixtures of mantle- and crust-derived melts, generated in the lower part of overthickened continental arc crusts. Debari also pointed out that the variation in geochemistry for these particular rocks exhibits some characteristics of adakites, although the magmas do not represent slab melts but simply were derived from a basaltic source. Here the tonalite is interpreted to be derived from garnet-bearing mafic granulite. In identifying topics for discussion, John Clemens asked the following questions: (1) In what tectonic setting do we get crustal growth? (2) What can we do with isotopic data? (3) Can felsic magma pond in the lower crust for periods ≥ 1 m.y. and interact extensively with mafic magma? (4) Do enclaves in granites reflect the sorts of mixing that might occur in the crust? In each of these questions, Clemens was drawing attention to the need for care in the interpretation of data gleaned from plutons emplaced in the upper crust when the magmas themselves were generated below the Moho, in the lower crust or by some combination of these sources, but some distance from the site of emplacement.

Another poster session addressed the role of hybridization by mixing and mingling and the petrogenesis of granites, as well as the relative roles of crustal stacking and radiogenic heating vs. basalt in providing the heat for crustal melting. The relationship between the extrusive products of crustal differentiation and their supposed intrusive equivalents was addressed in a study of the Fish Canyon magma, and the process of crustal differentiation in Cordilleran margins was contrasted with those that occur during orogenic collapse along collisional margins. Several posters addressed episodicity vs. continuity in tectonics and petrogenesis, and the roles of stress and lithospheric structure on processes of crustal differentiation.

Mike Sandiford addressed the question of continental heat flow and the role of radiogenic heat production in the crust in driving crustal differentiation. He emphasized how poorly we understand the three fundamental things we need to know: the vertical distribution of heat production; the heat production itself; and whether horizontal variability in heat production affects the response. This presentation emphasized the critical role played by concentration of heat production at particular levels within the crust, and how high continental heat flow observations do not require an enhanced mantle heat flux. On the contrary, Sandiford suggested that areas of high continental heat flow that result from a shallow concentration of heat production demand a lower mantle heat flux to avoid wholesale melting of the lower crust. Roger Powell introduced participants to THERMOCALC, a nonlinear equation solver that represents a powerful tool to investigate melting processes by forward modeling and calculation of phase diagrams. Mike Williams discussed geologic processes in the deep crust, with particular reference to the Snowbird tectonic zone, Canada. Williams emphasized that no matter what the history, slices of crust that cool isobarically at pressures appropriate to lower crustal conditions represent examples of the lower crust. Processes involved in the evolution of such slices of crust include underplating or intraplating, particularly through the involvement of basaltic dikes, and magma extraction, which relates to structural heterogeneities, involving both tectonic pumping of melt and opportunities for mixing between melts from different sources. He emphasized the heterogeneity of the crust and its overall block architecture.

Mike Dungan and Jon Davidson addressed the issue of crustal growth vs. crustal differentiation and emphasized that although we think of two end members (the mantle and the crust), most continental magmatism involves some interaction between these two. Underplating is a widely used term, but it is unclear why magma should pond at the Moho. Furthermore, we should remember that the average crustal composition requires a complementary mafic or ultramafic residue below the Moho. An important question is whether there are fundamental differences about the proportion of mantle and crustal contributions, the processes of magma generation, or the mechanisms of magma segregation, transport, and emplacement between large-volume silicic volcanic systems and Cordilleran batholiths. Perhaps, they suggested, there are no real differences, simply different perspectives based on different experiences. For example, although there is the same range of compositions in both volcanics and plutonics in continental arcs (basalt to rhyolite and gabbro to granite, respectively), the volcanic rocks are dominated by liquid processes whereas the plutonic rocks are dominated more by cumulate or intercumulate processes. In discussion, Allen Glazner emphasized the common chemical continuity within volcanic suites in contrast with the common chemical discontinuities within plutonic complexes.

Sue Debari and Alan Levander provoked further debate on the crustal composition paradox, the fact that the bulk composition of the continental crust is andesitic, whereas mantle additions to the crust in arcs are basaltic. In addressing the implied mass imbalance, three alternative explanations can be suggested. First, there may have been secular variation in plate tectonic processes leading to circumstances in which arcs include more basalt with evolution of the earth. Second, a mafic or ultramafic component may be hidden below the Moho; this could be of eclogitic composition or could comprise ultramafic cumulates. Third, a mafic or ultramafic component in orogens may have been lost by delamination. Bill Collins emphasized that modern Earth loses heat principally at plate boundaries and that orogens are thermally disturbed, structurally chaotic systems through which fluids, including melts, may pass. That such systems are open, he said, suggests that they may be dominated by disequilibrium rather than equilibrium processes, and the ultimate trigger for orogeny is likely to be in the mantle.

Jim Quick presented a model for the emplacement of the mafic complex in the Ivrea-Verbano zone based on detailed mapping over many years with several collaborators, extensive structural data and microstructural information, and numerical modeling. The model involves incipient extension of a continental crust, the start of emplacement of mafic magma leading to weakening and deformation under pure shear, the incorporation of melt-depleted granulite facies paragneiss septa within the mafic complex, and continuing deformation under left-lateral simple shear. Geochemical evidence in support of the model was presented by Silvano Sinigoi. Scott Barboza presented results of field work, petrology, and geochemistry designed to test the general model of underplating, as represented by the example of the mafic complex. He suggested that the regional-scale granulite facies metamorphism and depletion were not related to the mafic complex because the latter cuts discordantly the regional metamorphic isograds, the increase in regional metamorphic grade is related to increasing depth, not proximity to the mafic complex, the depleted granulites and septa within it exhibit similar levels of depletion, and the composition of leucosomes in migmatites immediately above it is inconsistent with the postulated composition of melt lost from the granulite facies terrane. Barboza concluded that widespread regional granulite facies metamorphism in the Ivrea-Verbano zone may not be directly related to the mafic complex as we now see it, and that mass and entropy balances derived from modeling likely represent minimum estimates of basaltic magmatism. Ernie Rutter presented a synthetic seismic reflection profile through the Ivrea-Verbano zone–Serie dei Laghi crustal section. Interestingly, imaged features correspond closely to those seen on many present-day seismic profiles, and the broad features of the tectonic evolution would be correctly interpreted. On the other hand, important recumbent fold structures would be missed, and relations between intrusive bodies and their country rocks would be unclear. Diane Clemens-Knott presented conclusions from her exhaustive oxygen isotope study of the mafic complex. Covariations between $\delta^{18}O$, SiO_2, Mg#, K_2O, and Ba require variable amounts of crustal assimilation and/or isotopic exchange, fractional crystallization, and mixing. She expressed the view that the Permian granites may have been generated by interaction of the voluminous main gabbro magma with a crustal melt containing less Sr. Interestingly, geochemical comparison between the mafic complex and similar xenoliths collected worldwide suggests that the complex is a close representation of deep crust in which mantle-derived magmas interact with high-^{18}O rocks.

Using the $^{207}Pb/^{206}Pb$ evaporation technique on zircon, Fernando Bea argued for a decrease in the age of regional metamorphism with increasing pressure, in the interval 290–260 Ma, interpreted to reflect cooling and crystallization of the partially molten lower crust at granulite facies conditions. In discussion, the importance of separating individual events in complex terranes and the difficulty of dating precisely peak metamorphic conditions were emphasized.

The final conference discussion considered the dynamic conditions for melt generation, ascent, and emplacement. George Bergantz emphasized the importance of the interplay between the perturbations to initiate crustal melting and the tectonic setting, or "plumbing," in dictating the style of melt movement. Both are necessary conditions for crustal differentiation. The subsequent group discussion was directed at three themes. First, what are the rheological and geochemical responses of crustal growth processes and how are they expressed in the rock record? Second, how are perturbations of the steady state generated, what are the rates of such perturbations, and do rocks preserve evidence of the perturbations and record the rates? Third was the issue of the global rates of mass transfer in the crust-mantle system, expressed as the input rate of mantle materials and the style and rates of return of mafic or ultramafic materials to balance the crustal composition.

Part of the difficulty in generalizing the observations from the field trips and the oral and poster presentations is that any given set of outcrops usually provides a two-dimensional view of a three-dimensional or even four-dimensional problem. As a result, many participants offered their comments as questions to the group. These included: Do melt-producing perturbations arise from "tectonics as usual" or from special mantle events? What is the form and rate of return of mafic or ultramafic material to the mantle? Is it in the form of abrupt delamination or drips? How does one tell whether a leucosome was ever a melt or magma. Are there unequivocal criteria, or even useful generalizations for identification of reaction products, cumulates or residual melt? Can the middle or lower crust be partially molten and retain that melt for extended periods (millions of years)? How much time is required for a basaltic underplate to cool, possibly hydrate, and become a candidate for subsequent melting? What is the temperature at the Moho? Is there a general form for the constitutive equations of reacting, multiphase mixtures? If basaltic underplating (or interplating) is important, why are there so few examples of basaltic intrusions significantly melting their margins? Is the dominant means of enthalpy transfer for crustal melting perhaps the result of dense networks of basaltic dikes ahead of a growing volume of basaltic material in sill-like bodies? Is the lower crust generally depleted? If magma chambers grow by sill-like additions at the floor, then why are near-vertical contacts so common between magma bodies and within magmatic complexes? Is the true lower crust ever exposed, or does its density prevent its occurrence at Earth's surface, with the consequence that the lowest crust we see exposed is not the lowermost crust at all? How does the Ivrea-Verbano zone compare to other supposed lower crustal sections?

ACKNOWLEDGMENTS

We are grateful for comments made to us by participants during and after the conference, and for a review by Phil Piccoli, but we take responsibility for any misperceptions or infelicities in this report.

We thank the Geological Society of America for sponsoring the conference and for providing funds to enable student participation, and the Petrology and Geochemistry Program of the National Science Foundation for provision of a grant to support travel by students.

Lois Elms (Western Experience, Inc.) arranged the general logistics, and Kate Walker dealt with the local organization and field trip logistics. We thank the field trip leaders and their associates, without whom the spectacular geology of the region could not have been presented in such a stimulating way.

Finally, we thank the participants themselves, for they provided the energy and the excitement. ■

Penrose Conference Participants

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Scott Barboza
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Jonathan Miller
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Phil Piccoli
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Jim Quick
Kent Ratajeski
Mary Reid
Ernie Rutter
Michel de Saint Blanquat
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Ed Sawyer
Urs Schaltegger
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Sheila Seaman
Silvano Sinigoi
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R. K. Smith
Gary Solar
Martin Streck
Alan Thompson
Simon Turner
Jean-Louis Vigneresse
Chris Wareham
Jennifer Watkins
Roberto Weinberg
Bob Wiebe
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COMMENTARY

The Pliocene–Pleistocene boundary should remain at 1.81 Ma

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Morrison and Kukla (1998) have asserted that the Pliocene-Pleistocene boundary (PPB) should be relocated at a level linked to a shift in the pattern of oxygen isotope cycles at ~2.6 Ma, a level identified with the GSSP (Global Standard Stratotype Section and Point) at the base of the Gelasian Stage. In challenging the validity of the 1.81 Ma PPB at Vrica, Calabria, despite its worldwide acceptance since it was ratified by the International Union of Geological Sciences (IUGS) in 1985, Morrison and Kukla relied on two premises: (1) that the Vrica boundary is not associated with a major climatic change, and is thereby erroneous; and (2) that this boundary is virtually uncorrelatable, in comparison with the 2.6 Ma level.

These premises are readily refuted (see Van Couvering, 1997). Both the 2.6 and 1.8 Ma climate steps are significant, but neither is uniquely definitive in the history of Cenozoic climate deterioration. Global correlation of the Vrica level with regard to magnetostratigraphy, paleontology, and cyclostratigraphy is easily as good, overall, as that of the Gelasian GSSP (Rio et al., 1998).

For 30 years, rear-guard resistance to the consensus favoring a "young" boundary such as Vrica has come mainly from a few who work in continental paleontology and paleoecology, in whose data the 2.6 Ma mid-Pliocene climate step is strikingly evident and who see this as the beginning of the "Ice Age." But in this instance, the rear guard has found aid in quoting current International Commission on Stratigraphy (ICS) policy that the main criterion for GSSPs is "unambiguous recognition and ease of correlation in as many marine and non-marine terrains throughout the world as possible." This marks a shift in officially sanctioned standards since the mid-1980s, from principles that emphasize definition over correlation to principles that emphasize correlation over definition. Remane (1997, p. 4) noted that "If the level at 2.6 Ma, favoured by many Quaternary stratigraphers, would considerably improve the correlation potential of the [PP] boundary, then a change should be seriously envisaged, but only then."

Encouraged by this statement, Morrison and Kukla claimed correlatabilty as a compelling reason for lowering the boundary to meet their paleoclimatic preconception. They offered to respect earlier, Hedbergian guidelines by making the base of the Gelasian Stage the base of the Pleistocene Series. This hierarchical nicety is more than ICS requires; preconceived series GSSPs are now being ratified with supposedly inherent and essential stage boundaries carelessly redefined to fit, or dispensed with altogether.

If correlation is all, what arguments remain against lowering the PPB to the level of 2.6 Ma? For example, placing the PPB below strata that have always been assigned to the Pliocene would normally be enough for stratigraphers to reject the 2.6 Ma proposal on first principles. Indeed, the original "Subappenine marls of Asti," recognized by Lyell in the designation of the Pliocene Series and thus excluded from the Pleistocene *by definition*, are of Gelasian age. In the ICS view, however, this argument is no longer irrefutable. As Cowie (1986, p. 78) wrote,"... choices in international stratigraphy should violate historical priority as little as possible: this consideration can often be overridden by the higher priority of going for the best and making progress. Confusing historical precedents may need to be set aside by an authoritative international decision, even though this may violate some established usage." We are concerned that the enthusiasm of ICS for "authoritative international decisions" that do not adhere to Hedbergian principles will lead eventually to a standard chronostratigraphic scale of pure expedience, in which the familiar terms that have served for over a century would become hollow shells devoid of any intrinsic content. In effect, this is to return to pre-Lyellian stratigraphy.

The most compelling reason, however, that the PPB must not be lowered, even if the correlation at 2.6 Ma is clearly superior to that at 1.8 Ma (which is not the case), is that this would make non-stratigraphic criteria part of the boundary definition. This endangers the very nature of the chronostratigraphic framework. The concept of the series as a chronostratigraphic unit was proclaimed at the International Geological Congress in Bologna (1881). Its nature has remained unchanged, as an expression of the profound idea that the time correlation of rocks provides an intrinsic temporal framework for historical geology. The integrity of the series is based on its direct relationship to the rock record. Subjective interpretations, whatever their nature—climatic, tectonic, paleobiologic, oceanographic—should never become the means for defining a series, under the principle that the object of measurement cannot also be the tool of measurement. Morrison and Kukla believe that the PPB should be defined so as to "have significance in the glacial and climatic history," in order to be "a true climatostratigraphic boundary that represents a major shift in global air, ocean and land climate systems." In no instance, we believe, should a chronostratigraphic boundary be selected with such criteria as these.

In our view, the proposal for lowering the PPB is misconceived, and it also exposes a trend toward a destabilizing laxity in chronostratigraphy. Indeed, ICS should already have dismissed this same proposal when it was formally presented to the Subcommission on Quaternary Stratigraphy in Berlin in 1995. On the contrary, this proposal is being put to a postal ballot of the Neogene and Quaternary Subcommissions of ICS and, if a majority favors the change, to a vote of the full ICS. We can only hope that this perennial campaign to set aside principles in favor of attractive expediency will end in the course of this formal procedure.

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