Exhumation Processes: Normal Faulting, Ductile Flow, and Erosion

Conveners:
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Over the past 25 years, there has been a growing appreciation of the role that tectonic processes play in exhuming metamorphic rocks. This trend began with the discovery of highly attenuated crustal sections in the Basin and Range province and the recognition that attenuation was caused by regional-scale horizontal extension, as manifested by normal faulting. This discovery caused many geoscientists to rethink the role that horizontal extension or, as it is more commonly called, tectonic extension, might play in other orogenic settings. Of particular interest is emerging evidence that tectonic extension might be responsible for exhuming metamorphic rocks within convergent orogens, such as onland thrust belts (e.g., Himalayas, European Alps, Betic Cordillera of southern Spain, Brooks Range of Alaska) and subduction-related convergent margins (e.g., Franciscan of California, Sanbagawa of Japan, Hellenic-Aegean convergent margin of Greece, Hikurangi accretionary wedge of northeastern New Zealand).

We use the term "exhumation" to refer, in a generic way, to all processes that contribute to the unroofing of deeply seated rocks and their rise to the Earth's surface. There are several exhumation processes. Normal faulting and extensional ductile flow operate within the Earth and are a direct manifestation of tectonic deformation, whereas erosion operates at the Earth's surface but can be indirectly influenced by tectonically driven changes in topography.

One of the most difficult questions to answer in most orogenic belts, especially the older ones, concerns the relative contributions of these different exhumation processes. Even so, the tectonics community has moved toward a casual consensus that normal faulting is the primary mechanism for exhumation of deeply seated rocks. The most commonly cited evidence is the presence of "younger-over-older" relationships, where large faults, with low to moderate dips, have placed younger rocks on older rocks or lower grade rocks on higher grade rocks and, in the process, have cut out significant thicknesses of stratigraphic or metamorphic section. But recent papers have shown that this type of evidence, by itself, is not diagnostic. Contractional faults can also cut out section if the section was tilted back toward the hinterland prior to faulting. A typical contractional fault would climb upward toward the foreland but would appear to cut downward through the tilted section. Top-to-the-foreland motion would produce the appearance of normal offset where the fault cut through the tilted section. An additional problem is that the total offset and original dip of most crustal-scale normal faults, especially those involving deep crustal rocks, are typically poorly resolved. All of these factors make it difficult to quantify the relative contribution of normal faulting in exhuming deeply seated rocks.

Despite the current preference for exhumation by normal faulting, it is clear that ductile flow and erosion must play some role. Penetrative deformational fabrics are present in most exhumed mountain belts and provide clear evidence that ductile flow is an important process that can either increase or decrease the rate of exhumation, depending upon whether the flow causes thinning or thickening in the vertical direction. Erosion is also an important exhumational process, as indicated by the large volumes of sediment found adjacent to most contractional orogens.

Within this context, we organized a Penrose Conference to examine all processes that contribute to exhumation of deep-seated rocks in ancient and modern orogens. We started with three broad objectives: (1) to review and synthesize our knowledge about normal faulting, ductile flow, and erosion as exhumation processes; (2) to examine the geologic evidence needed to quantify the relative contributions of these different processes, using information from metamorphic petrology, isotopic thermochronology, structural and kinematic analysis, synorogenic stratigraphy, geomorphology, and paleoelevation analysis; and (3) to examine relevant geodynamic models and their predictions for conditions that might trigger gravitational collapse.

THE CONFERENCE

The conference was held October 9–13, 1996, at the Orthodox Academy of Greece, located near the town of Chania on the island of Crete in southern Greece. It included three days of presentations and two days of field trips. There were 94 participants, 42 from the United States, 15 from England, 13 from Germany, five from Australia, four each from Greece and Canada, three from Switzerland, and one each from France, Israel, Japan, The Netherlands, New Zealand, Norway, Poland, South Africa, and Spain. The participants included 16 Ph.D. students. The conference had a relatively large number of women participants, 13 professionals and 9 students, marking a positive trend

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PARTICIPANTS

Torgeir B. Andersen	Jean Crespi	Herman Grütter	Karen L. Kleinspehn	Alan Roberts	Stuart Thomson
Vaios Avdis	George H. Davis	Larry Guenther	Maarten Krabbendam	David Rowley	Robert J. Twiss
Hans G. Avé Lallemant	John F. Dewey	Bradley Hacker	Anthi Liati	Leigh Royden	O. Vanderhaeghe
Dov Avigad	Bill Dinklage	Bernard Hallet	Gordon S. Lister	Elizabeth Schermer	Jaume Vergés
Gary Axen	David Dinter	Andreas Henk	Lidia Lonergan	Fried M. Schwerdtner	Lisa A. Verts
Suzanne Baldwin	Theodor Doutsos	Ralf Hetzel	Neil Mancktelow	Jane Selverstone	Simon Wallis
Samantha Barr	W. Gary Ernst	Paul Hoffman	Stanislaw Mazur	Dianne Seward	Nicole Wawrzenitz
Manfred Brix	Hilmar von Eynatten	Daniel K. Holm	Peter Molnar	Eberhard Seidel	Laura E. Webb
Fraukje Brouwer	James Faulds	Niels Hovius	Patrick O'Brien	Sarah Sherlock	John Weber
Doug Burbank	Paul Fitzgerald	Simon Inger	John S. Oldow	Virginia B. Sisson	John Wheeler
B. Clark Burchfiel	Marnie Forster	Carl Jacobson	John P. Platt	Colin Stark	Donna L. Whitney
Erin Campbell	David Foster	Rebecca A. Jamieson	Raymond A. Price	Bernhard Stöckhert	Sean D. Willett
Christian Chopin	Wolfgang Franke	Barbara E. John	Meinert K. Rahn	John Tarney	Paul F. Williams
Peter Copeland	Wolfgang Frisch	Christopher Johnson	Tim Rawling	Micheal P. Terry	Brian Windley
Meg Coleman	Dieter Gebauer	Sue Keay	Steve Reddy	Christian Teyssier	
	Allen F. Glazner	Adiamantis Kilias	Stephen J. Reynolds		

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in the reduction of the gender gap, at least in the area of exhumation research.

Presentations were divided into six half-day sessions. Each session had about two hours of oral presentations, about one hour of poster presentations, and about one hour for a panel discussion. This report highlights the oral presentations and panel discussions. Those who are interested in further details will find a complete listing of the conference program, including the titles of all presentations, at the following Web site: http://love.geology.yale.edu/~brandon/exhume.html.

FIELD TRIPS

The field trips were led by Bernard Stöckhert (Ruhr-Universität Bochum, Germany) and Eberhard Seidel (Universität zu Köln, Germany), and focused on geologic evidence for Miocene exhumation in a convergent-margin setting. The island of Crete is a forearc high that formed above the south-facing Hellenic subduction zone. The island has spectacular exposures of high-pressure–low-temperature (HP) metamorphic rocks that formed at depths of ~35 km and were exhumed rapidly, starting in the Miocene. Geodetic data and the presence of young normal faults indicate that the surface of the island is being extended in a strike-normal direction, presumably due to southward rollback of the subducting slab. Extensional deformation on Crete is commonly viewed as a southern manifestation of the active extensional province that underlies the Aegean Sea to the north. But an important distinction is that Crete lies in the forearc above the Hellenic slab, whereas the Aegean metamorphic core complexes have formed in the arc and back-arc regions.

At present, Crete has very rugged topography, with local relief >2 km (highest point is Psiloritis at 2456 m). The rugged landscape suggests rapid erosion rates, but the relative contribution of erosion to total exhumation remains poorly resolved. This problem was a common theme throughout the conference.

SESSION 1: LOCAL EXPRESSION OF TECTONIC EXHUMATION: STRUCTURE, METAMORPHISM, AND THERMOCHRONOLOGY

Mark Brandon opened the conference with a short introduction. He made the point that exhumation rates alone are not diagnostic of process. A common assumption is that tectonic exhumation is fast and erosion is slow. But erosion has been clocked at rates up to ~15 mm/yr[1] (e.g., Southern Alps of New Zealand). Conversely, there are settings , such as long-lived continental rifts, where tectonic exhumation probably operates at very slow rates. Other evidence is needed to distinguish between tectonic and erosional exhumation.

John Platt followed with a keynote presentation on synexhumation deformation in mountain belts. He reviewed geologic evidence for detecting tectonic exhumation, the main clues being the excision of metamorphic gradients, the shape of pressure-temperature-time (P-T-t) paths, and the kinematics of ductile shear zones and brittle faults.

Jane Selverstone challenged the use of P-T-t paths to distinguish exhumational processes. The shape of a P-T-t path is typically difficult to resolve, and the youngest part of the path, which is most diagnostic of process, is the most difficult to constrain. She emphasized her point by showing two sets of published P-T-t paths, one set attributed to erosion and the other to tectonic exhumation. There was no obvious difference between the sets. The inference is that steep decompression curves should not be considered diagnostic of extensional exhumation.

Clark Burchfiel reviewed the development of the South Tibetan detachment system, a north-dipping system of faults and ductile shear zones with top-north offsets that crops out for more than 700 km along the southern flank of the Himalayan crest. The detachment system has probably been active since 22 Ma and appears to have evolved diachronously along its length. There is local evidence in the Mount Everest area that the detachment system caused rapid exhumation, but at present it is not known if this is a general feature of the entire system.

Steve Reddy reviewed the pitfalls in recognizing extensional faults. He showed an example from the Pennine zone of the Swiss Alps where metamorphic section was thinned by a doubly vergent system of extensional faults that moved top-northwest and top-southeast.

The panel, chaired by Ray Price, focused on the correct use of kinematic indicators and on the distinctions between strain and displacement and between crystallization ages and cooling ages. There was also some discussion about the difficulties in using time-temperature data to estimate a time-depth path. One panelist noted that the present northward dip of the South Tibetan detachment system could be caused by isostatic uplift associated with deep erosion of the high Himalayas. This possibility highlighted the general difficulties in resolving the original dip of exhumational structures.

SESSION 2: FORMATION AND EXHUMATION OF UHP METAMORPHIC ROCKS

The most intriguing examples of deeply exhumed rocks are the ultra-high-pressure (UHP) metamorphic rocks, first found in the Alps and the Norwegian Caledonides, and now known from numerous places around the world. UHP metamorphic rocks are continental or oceanic crustal rocks that were metamorphosed within the coesite-eclogite or diamond-eclogite facies. P-T-t data for these rocks demonstrate that both oceanic and continental crust can be subducted to depths >100 km and then returned to the surface.

The keynote presentation by Christian Chopin provided a general review of the UHP problem. Simon Wallis described some UHP rocks from China and then explored the role that buoyancy might play in returning these rocks to the surface. Paddy O'Brien discussed attempts to determine the P-T-t path for HP metamorphic rocks in the Bohemian massif of Germany.

Dieter Gebauer reviewed his application of SHRIMP U-Pb dating to determine ages of igneous and metamorphic growth of zircons from HP and UHP metamorphic rocks of the Alps. His work indicates an Eocene age for metamorphism which would require exhumation rates of ~10 to 30 mm/yr for some of the Pennine nappe. A major problem, however, is that, as of yet, there is no direct tie between Gebauer's zircon ages and the formational ages of the diagnostic HP and UHP metamorphic assemblages.

The panel, chaired by Gary Ernst, emphasized that UHP rocks are typically found as large, internally coherent slices at least several kilometers wide. The preservation of UHP assemblages suggests dry metamorphic conditions during exhumation. Tectonic extrusion was reviewed as one way to account for the exhumation of these unusual rocks.

General comments from the floor highlighted several additional issues. Are UHP rocks metamorphosed above the Moho within a very thick crustal root or below the Moho as slices subducted into the mantle? The paucity of mantle rocks in association with UHP rocks favors the crustal-root option. But the mantle option is favored by the observation that crustal rocks are not strong enough to support the exceptional high topography that should form above a region underlain by very thick (>100 km) continental crust. A thick crustal root would be further inhibited by the higher radiogenic heat production typical of continental rocks, which should lead to thermally induced softening and/or melting. For the modern Earth, continental crust is thought to be no thicker than about 60 to 70 km. But what defines the Moho in areas where the crust has been metamorphosed to UHP assemblages? A study of the seismic-velocity properties of UHP rocks is needed to understand the relationship of the seismically determined Moho to the petrologically defined base of the crust.

What is the role of buoyancy in returning metamorphosed crustal rocks to the surface? Chopin indicated that the UHP granitoid rocks found in the Pennine nappes of the Alps have densities of 2840 to 3080 kg/m^{-3}. These rocks would be buoyant with respect to the mantle but not with respect to average continental crust. The buoyancy argument is further challenged by the discovery of ultramafic rocks with UHP assemblages (e.g., metamorphic diamonds in the Beni Bousera and Ronda peridotites of Morocco and southern Spain; >120 km assemblages from the Alpe Arami garnet peridotites in the Alps).

SESSION 3: RATES AND PATTERNS OF LONG-TERM EROSIONAL EXHUMATION

Most currently cited erosion rates are estimated from short-term (10–50 yr) studies of sediment yield from modern river drainages. A nagging question is whether or not these rates are representative of long-term erosion rates. This problem is particularly important for the Quaternary because global climate has been fluctuating on a period of ~100,000 yr due to the glacial cycle. In this context, long-term erosion rates can be usefully defined as the average rate of erosion for a period of time >~0.1 m.y., to ensure that the effects of the glacial cycle are averaged out.

In his keynote presentation, Doug Burbank reviewed various methods for estimating long-term erosion rates, such as the reconstruction of eroded geologic features, isopach measurements of synorogenic sediments, thermochronologic dating of exhumed bedrock or detrital grains in synorogenic sediments, or an inventory of erosional processes operating within a modern drainage. Burbank cited geologic evidence indicating that the Salt Range of Pakistan was eroded at long-term rates of 5 to 10 mm/yr.

Peter Copeland discussed the interpretation of cooling ages for detrital grains derived from the Himalayas. The large volume of sediment in the Himalayan foreland and in the offshore Bengal and Indus fans provides an important record of erosional exhumation for the Himalayas. Paul Fitzgerald reviewed fission-track data that indicate long-term erosion rates of ~2 mm/yr for Denali (Mount McKinley) in southern Alaska.

David Rowley described the exhumation history of UHP rocks in Dabie Shan, China, where exhumation rates are estimated to have been 3 to 11 mm/yr. He presented a variant of the tectonic extrusion model, where UHP rocks moved upward as a large tabular body, with the relative motion resolved along a lower thrust fault and an overlying normal fault. The front of the extruded body is eroded back at a rate close to the extrusion rate. This type of model emphasizes the fact that exhumation is not necessarily restricted to vertical motions and may also involve the interaction between erosional and tectonic processes.

The panel, chaired by Karen Kleinspehn, highlighted several additional issues. To what degree are erosion rates controlled by climate? When using thermochronometry, how can one account for the effects of topography on isotherms and the rotation of isochronal surfaces after isotopic closure? How much of the exhumation history of a UHP terrane is preserved in its present structural and stratigraphic setting? Do shallow-level structures bear any relations to the processes associated with the early phases of exhumation when the rocks were still at great depths?

SESSION 4: PROCESSES AND CONTROLS OF LONG-TERM EROSIONAL EXHUMATION

Geomorphology continues to provide fundamental information about erosional processes, but much of this research remains at an early stage of development. In particular, there are many unanswered questions about how short-term local-scale erosional processes relate to the long-term erosional behavior of a whole mountain range. Nonetheless, this research is essential for resolving the interplay between tectonics, topography, global climate change, and regional-scale erosion.

Bernard Hallet gave a keynote presentation in which he compared modern rates of erosion in glaciated and nonglaciated active mountain belts. He noted that nonglaciated mountainous drainages in Asia and New Zealand have modern erosion rates of about 1.5 to 8 mm/yr, which overlaps with exhumation rates estimated for UHP rocks. He then went on to show that warm-based alpine glaciers in southern Alaska had erosion rates of 5 to 80 mm/yr. This observation suggests that increases in alpine glaciation, which could be caused by global cooling, increased precipitation, and/or growth of mountainous topography, could play a major role in exhumation of metamorphic rocks and in limiting the maximum height of mountains.

Sean Willett reviewed the results of numerical models of orogenesis that account for both deformation and erosion. He emphasized that deformation and erosion are strongly coupled, so that their relative effects on the orogenic system may be difficult to separate.

Niels Hovius presented the results of a regional-scale inventory of landslides in the Southern Alps of New Zealand as observed over the past several decades. He estimated that erosion due to landslides was occurring at rates ranging from 5 to 18 mm/yr. Earthquakes seem to be the primary factor in triggering the landslides; climate has played a subsidiary role.

The panel, chaired by Paul Hoffman, considered a range of topics. What factors are most important for determining when a tectonically active landscape reaches steady state? In this context, steady state means that the rates of rock uplift are balanced by equal rates of erosion. Is the time to steady state typically short (<1–2 m.y.)? In that case, the geomorphic system would closely track tectonic uplift. Or is the time to steady state typically long (>10 to 20 m.y.)? If so, the geomorphic system would be constantly out of phase with tectonic uplift. This question is critical for resolving the cause of the increased flux of terrigenous sediment to the world's oceans during the Quaternary, whether due to climate change or to increased rates of tectonic convergence.

One panelist presented a comparison of the exhumational history of the Tauern window, which is the most deeply exhumed part of the eastern Alps, with the record of erosional exhumation preserved in the Alpine foreland and offshore basins beneath the Mediterranean and the North Sea. An integrated sediment budget showed that orogenic sedimentation rates were low when the Tauern window was being exhumed. The inference was that tectonic processes probably dominated during deep exhumation of this part of the Alps.

Another panelist showed that fast erosion can have a profound influence on the shape of metamorphic isograds and, in some cases, can result in inverted isograds.

SESSION 5: THE ULTIMATE CAUSE FOR TECTONIC EXHUMATION: ACTIVE RIFTING VS. PASSIVE GRAVITATIONAL COLLAPSE

Tectonic exhumation has been recognized as a common factor in continental orogenesis, but the cause remains poorly understood. Is it a result of far-field displacements, as postulated for the back-arc stretching that formed the Aegean metamorphic core complexes, or is it due to collapse of overthickened crust, as has been suggested for the Himalayan-Tibetan orogen?

In his keynote presentation, Gordon Lister stressed the importance of far-field displacements. For the Aegean, he argued that back-arc stretching was caused by rollback of the subducting slab. He also emphasized the transient nature of metamorphism in extensional settings.

Leigh Royden showed how convective flow in thickened crust might account for deformation of the Tibetan plateau. She argued that the style of deformation in a convergent orogen is controlled by the average strength of the crust, parti-

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tioning of strain, and the degree of coupling between the crust and mantle.

John Dewey presented evidence that UHP rocks of the Western Gneiss region in the Norwegian Caledonides were exhumed tectonically during oblique continent/continent collision. Exhumation rates were estimated to have been ~10 mm/yr. He discounted erosion exhumation because basinal strata that overlie the Western Gneiss contain no HP or UHP detritus. Dewey also noted that the Western Gneiss was subjected to extreme vertical shortening, locally as much as –75%, which indicates that ductile thinning was probably an important factor in exhuming these rocks.

The panel discussion, chaired by George Davis, started with the comment that the Kapuskasing uplift of Canada, which exposes deep-seated Precambrian crust, may provide a particularly well studied example of gravitational collapse. The panel then considered some more speculative questions. Would the exhumational phenomena be better understood by dividing the tectonic setting on the basis of the "absolute" motion of the upper plate? For instance, did the upper plate retreat (Aegean), advance (Alps), or surrender (lithospheric delamination in the Himalaya)? Is fault dip related to tectonic process, with gravitational collapse producing gently dipping normal faults and rifting resulting in moderately dipping normal faults?

SESSION 6: INFLUENCE OF DEEP-SEATED PHENOMENA ON THE GEODYNAMIC EVOLUTION OF MOUNTAIN BELTS

Deep-seated processes have also been proposed as important factors controlling exhumation in mountain belts. In particular, there has been much emphasis on thermal softening of an orogenic root and delamination of a thickened mantle root. Thermal softening would reduce the strength of the crust, and mantle delamination would increase the average topography of the orogen. Both phenomena could lead to gravitational collapse.

The theme of Peter Molnar's keynote presentation was that normal faulting is typically initiated by some major change in the geodynamic system, such as a change in boundary conditions (e.g., plate motions), a change in the constitutive behavior of the crust (e.g., thermal softening), or a change in the position of rocks relative to a heterogenous stress field. He then reviewed the current understanding of Rayleigh-Taylor instabilities in thickened lithosphere, which might explain the conditions needed for mantle delamination. This type of instability has been investigated using analog models, but the characteristic time and length scales of the instability in the real mantle remain poorly understood. Molnar finished with an overview of a current project that combines paleobotany with meteorology to estimate paleoelevation, with the objective to resolve the uplift history of the Colorado Plateau and other high-elevation areas.

Alan Glazner and John Tarney reviewed how magmatism might influence extensional deformation. Glazner focused on buoyancy of magmas and their level of emplacement in the crust. Tarney discussed how magmatism might trigger crustal extension.

The panel, chaired by Neil Mancktelow, started with a discussion about the concept of gravitational potential energy for understanding conditions leading to gravitational collapse. This was followed by two questions. How does magmatism affect deformation and heat transfer during extension? What is the relationship of UHP metamorphism to magmatism?

SUMMING UP

The meeting ended with summaries from the panel chairs. The general consensus was that the conference succeeded in providing a broad overview of the exhumation problem. In particular, it is clear that in most active mountain belts, erosion and tectonism are dynamically coupled to the point where it may be difficult to separate cause and effect. It appears that erosion can operate at very fast rates, perhaps as high as 15 mm/yr, given sufficient precipitation, steep terrain, and/or extensive alpine glaciation. These rates could be sustained for long periods of time, as long as uplift rates continued to match erosion rates and climate conditions remained favorable for fast erosion. Alpine glaciation appears to be the most aggressive agent of erosion, one that is particularly sensitive to global climate. In this regard, the relatively high sediment production rate of the Quaternary may be the result of a cooler climate and more extensive alpine glaciation. A problem, however, is that much of our current understanding of erosion rates is based on relatively short records. There is a serious need for better long-term estimates using the sediment inventories or thermochronometry.

Buoyancy remains an often-cited factor for return of HP and UHP rocks to the surface, but there are an increasing number of examples where relatively dense rocks have been exhumed. Geologists have generally accepted the possibility that subduction is able to carry continental crustal rocks to depths >100 km, perhaps because the driving force involves the negative buoyancy of subducting oceanic lithosphere. What remains conceptually difficult is how tectonic forces can return rocks to the surface, especially relatively dense eclogite-facies rocks and mantle peridotites. The presence of these rocks at the Earth's surface suggests that accretionary wedges must have sufficient upward flow to overcome the negative buoyancy. This inference implies that buoyancy is not a significant rate-limiting factor in the exhumation of metamorphic rocks.

The conference highlighted some major challenges in understanding the origin of UHP rocks. One important issue concerns the relationship of the petrologic Moho to the seismic Moho in areas with anomalously thick continental crust. Another concerns the tectonic setting in which UHP metamorphic rocks are formed. For instance, where would one expect to find these rocks forming today? If UHP metamorphism occurs while crustal slices are in the mantle, then this phenomenon may be unrelated to tectonic processes that thickened the crust.

IN MEMORIAM

Just prior to the conference, one of the student participants, Steve Thornley, was killed in an accident in the Himalayas. Steve had been invited to give a presentation at the conference. He had just finished a Ph.D. under Dick Walcott at Victoria University, Wellington, where he studied extensional deformation operating at the surface of the Hikurangi accretionary wedge, New Zealand. We were saddened by the death of this promising young scientist.

ACKNOWLEDGMENTS

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