We're Almost There!
See p. 3

Vol. 8, No. 12 December 1998

GSA TODAY

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INSIDE

If the Strong Crust Leads, Will the Weak Crust Follow?

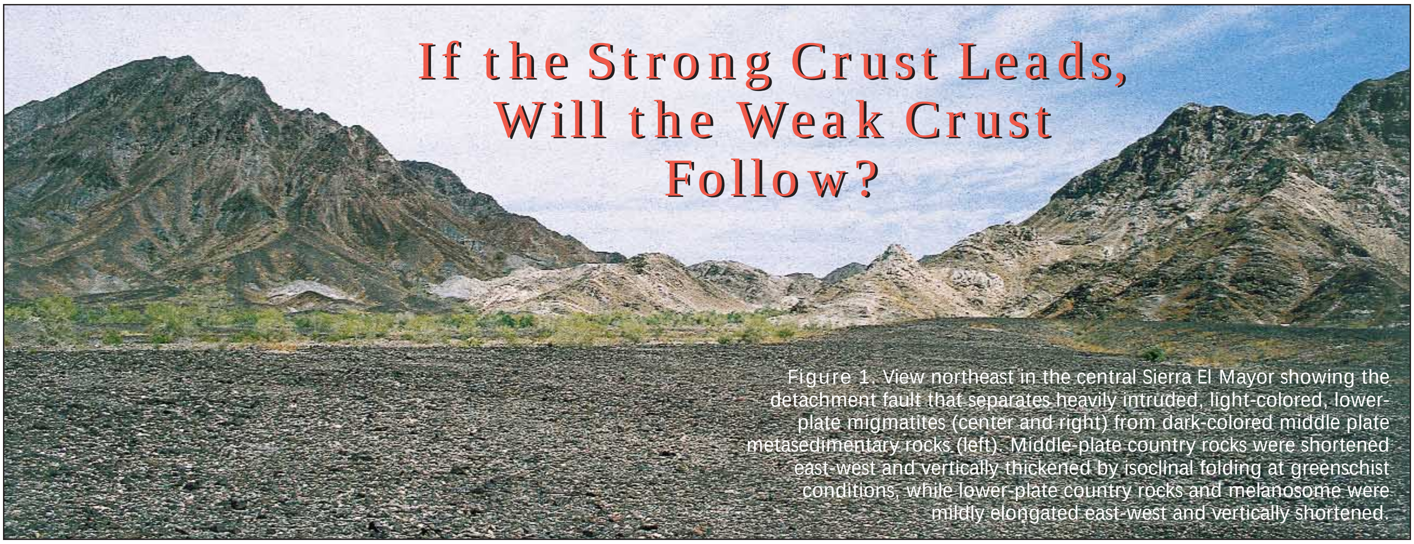

Figure 1. View northeast in the central Sierra El Mayor showing the detachment fault that separates heavily intruded, light-colored, lower-plate migmatites (center and right) from dark-colored middle plate metasedimentary rocks (left). Middle-plate country rocks were shortened east-west and vertically thickened by isoclinal folding at greenschist conditions, while lower-plate country rocks and melanosome were mildly elongated east-west and vertically shortened.

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ABSTRACT

Contemporaneous deformation at different levels of the continental crust can be strongly heterogeneous, resulting in disparate bulk deformation patterns between crustal levels. In each of three examples from diverse tectonic settings, exposed rocks from different crustal levels differ greatly from one another in strain geometry. Such heterogeneity of deformation is likely to be controlled by rheological differences and boundary conditions. If strong three-dimensional heterogeneity of strain in deforming continental crust is the norm rather than the exception, many assumptions commonly used in interpretation of vertical profiles of modern and ancient crust, in dynamic and kinematic modeling, and in inference of ancient plate motions could be inappropriate.

INTRODUCTION

It has long been known that rock deformation patterns vary greatly with rock type, temperature, pressure, strain rate, differential stress, and fluid conditions, among other controlling factors. Spatial and temporal variability of any of these factors leads to heterogeneous strain on a variety of scales, ranging from that of lithospheric plates to individual thin sections.

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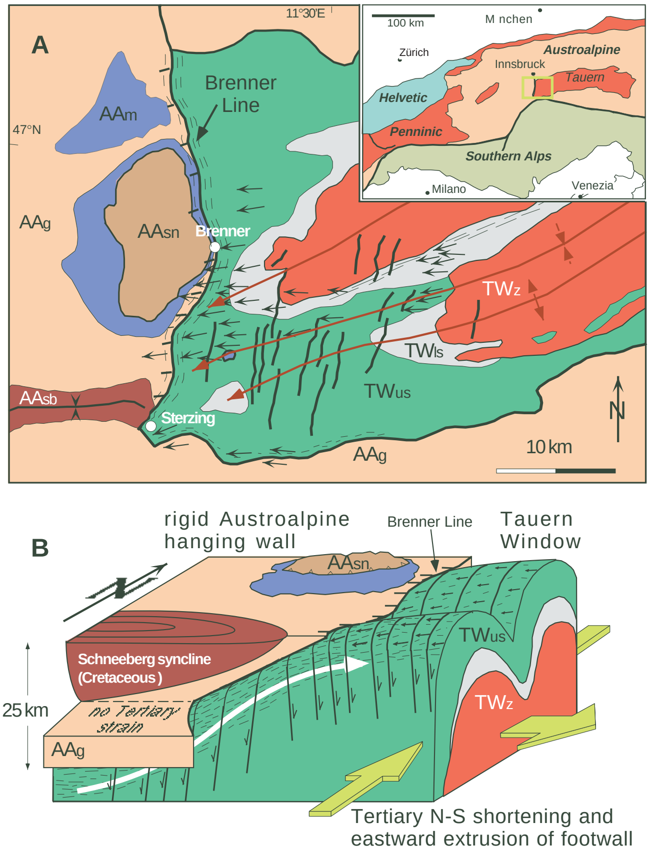

Figure 2. Tectonic map (A) and block diagram (B) showing key features of the Brenner Line footwall (Tauern window) and hanging wall (Austroalpine units); yellow box in inset shows location. Footwall units are Zentralgneis basement (TWz) and Lower and Upper Schieferhülle cover sequences (TWls and TWus); Austroalpine units are gneisses (AAg), Mesozoic cover (AAm), metasedimentary rocks of the Schneeberger syncline (AAsb), and overthrust Steinach nappe (AAsn). Deformation and metamorphism in AA units predate 70 Ma. Ductile mylonites, upright folds, and high-angle normal faults in the Tauern window developed during Oligocene-Miocene extrusion.

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IN THIS ISSUE

In Memoriam

John L. Burnett
Sacramento, California
September 1998

Willard C. Gere
Menlo Park, California
September 20, 1998

Clyde T. Hardy
Logan, Utah
October 13, 1998

Ruth Hopson Keen
Portland, Oregon
October 17, 1998

Gerhard W. Leo
Los Gatos, California
September 14, 1998

Ronald J. Lipp
Long Island, New York
September 11, 1998

James B. Rucker
Carriere, Mississippi

William V. Sliter
Menlo Park, California
October 1997

William G. Wahl
Corbyville, Ontario
July 10, 1998

Crust *continued from p. 1*

The most important boundary at the plate scale could be the rheological gradient that decouples rigid lithosphere from weaker underlying mantle asthenosphere (e.g., Karato and Wu, 1993) and allows major differences between their motions. This nearly complete decoupling leads to a situation where three-dimensional lithospheric-plate velocity fields are known with centimeters-per-year precision, but comparative motions of the underlying upper mantle are very poorly known (e.g., Montagner, 1994).

Continental crust is also mechanically and rheologically stratified, some crustal levels being weaker and less rigid than others (e.g., Brace and Kohlstedt, 1980). Weak lower or middle crust can allow decoupling of upper crust from underlying mantle (e.g., Molnar, 1988; Hopper and Buck, 1998) and probably affects deformation style(s) of the continental crust as a whole (Buck, 1991; Royden, 1996).

Different strain magnitudes and geometries can develop coevally between different crustal levels as a result of rheological stratification. These differences are difficult to observe, but we believe that they are common, if not typical, in tectonically active regions. Nevertheless, strain characteristics of one crustal level are commonly extrapolated to other crustal levels, compared in two-dimensional vertical profiles, or used to infer major orogenic motions and past plate motions.

We discuss three examples of contrasting coeval deformation patterns between different crustal levels and consider their implications for vertical profiles, dynamic models, and inferences of relative plate motions. Our examples are from diverse settings, including a continental collision zone (Alps), an accretionary prism (Japan), and a convergent-margin batholith (Baja California; Fig. 1).

EXAMPLE 1—TAUERN WINDOW, EASTERN ALPS

The Alps formed in response to roughly north-south convergence between Eurasia and the Adriatic microplate in latest Cretaceous through mid-Tertiary time. Convergence resulted in closure of the Tethys ocean and partial subduction of European continental crust. Syncollisional, orogen-parallel extension, as in the Brenner area (Fig. 2), was important (Behrmann, 1988; Selverstone, 1988; Ratschbacher et al., 1991; Mancktelow and Pavlis, 1994). The footwall of the Brenner Line underwent strong constrictional strain during Tertiary orogenesis, whereas the hanging wall remained essentially rigid.

The Brenner Line normal shear zone marks the western margin of the Tauern window, which is a metamorphic core complex exposing middle and lower crustal schists and gneisses of European affinity beneath the structurally higher Adriatic plate (Austroalpine nappes; Fig. 2A). The north and south margins of the window are dominated by left-lateral and right-lateral zones, respectively, and rocks of the western window were extruded upward and eastward (Ratschbacher et al., 1991; Fig. 2B). The Brenner shear zone excised >10 km of crust during 30 to 60 km of top-to-west slip (Axen et al., 1995).

Despite juxtaposition during collision, Tauern and Austroalpine rocks record very different metamorphic histories. Footwall rocks reached high-pressure, greenschist-to-amphibolite facies metamorphic conditions between 30 and 20 Ma (Blanckenburg et al., 1989; Christensen et al., 1994) in response to Austroalpine overthrusting (Selverstone, 1985). In contrast, the hanging-wall rocks attained medium-pressure metamorphic conditions before 70 Ma (Frank et al., 1987).

Structural differences also exist across the Brenner Line normal fault. Footwall rocks are highly sheared and recrystallized (mylonitized) for several kilometers (Fig. 2) below the Brenner Line, with common top-to-west shear indicators (Selverstone, 1988; Axen et al., 1995). Rocks and early-formed mylonites (35 to 30 Ma; Christensen et al., 1994) exposed in the western Tauern window are folded into two upright, large-amplitude antiforms (Lammerer and Weger, 1998; Selverstone, 1988). These mylonites are overprinted upward by younger top-to-west mylonites that become less folded as the Brenner Line is approached, and the Brenner Line itself is broadly warped by large folds (Axen et al., 1995). These observations indicate that north-south convergence continued during east-west extension and unroofing of the Tauern window.

Syn- to postmylonitic, high-angle normal faults are abundant within the footwall near the Brenner Line (Fig. 2). These faults probably formed in response to buoyancy forces induced by unroofing, and they have both west- and east-down displacements (Axen et al., 1995). Fluid-inclusion data show that west-down faults were active at 15–25 km depth, whereas east-down faults later affected the same rocks at 3–8 km depth (Selverstone et al., 1995). Footwall exhumation processes from ~25 to 5 km were thus both ductile and brittle. We infer that Brenner Line slip, mylonitization, antiform growth, and high-angle faulting were coeval in mid-Oligocene to late Miocene time (Selverstone, 1988; Selverstone et al., 1995; Axen et al., 1995).

In contrast, the Austroalpine hanging wall is essentially unextended internally. Mylonites are locally present 200 m above the Brenner Line (Selverstone, 1988), but

Crust *continued on p. 4*

Support Your Society—The Sequel

Gail Ashley, President, Geological Society of America

Two years ago Eldridge Moores, who was then president of GSA, wrote eloquently about the vital importance of members' support of GSA's Second Century campaign. At that time, in September 1996, contributions to the campaign amounted to $4.7 million. Since then, the total has nearly doubled and now stands at more than $9.3 million.

As your current president, I am privileged, both for myself and on behalf of my predecessors in office during the campaign, to applaud this wonderful commitment to GSA's activities and influence. The generosity of GSA's members and friends has brought us to within $700,000 of our campaign goal. More important, this generosity has had a measurable impact on the growth and success of GSA's programs of education and outreach.

Two years ago, Eldridge Moores described GSA's emerging plan to ensure better efforts and results in communicating the crucial importance of the geosciences to society. I am pleased to report that in every area of targeted activity, the volunteer and financial support of GSA's membership has made measurable differences. The activities Eldridge outlined were:

New efforts to enhance GSA's publications. The fundamental goal of the publications program is to serve individual members as well as the academic, research, and applied geoscience communities. Owing to the dedication of GSA's editors and the headquarters publications staff:

- *Geology* has held its place as the foremost journal in its field and draws a wide range of manuscripts.
- The *GSA Bulletin* remains one of the most frequently cited journals of geoscience.
- GSA has successfully co-ventured with the Association of Engineering Geologists in publishing the journal *Environmental and Engineering Geoscience*.
- *GSA Today* has broadened its contents, and readers have responded enthusiastically.
- Increases in nonmember subscription prices have put the publications program on a sound fiscal footing.

Science Awareness through Geoscience Education (SAGE). This program's ambitious plans have become reality, and new plans are being made.

- The Earth and Space Science Technological Education Project has completed two series of highly successful summer workshops for middle school science teachers to help them integrate earth science into their curricula.
- Geological Education through Intelligent Tutors has produced its first multimedia earth science CD-ROM, "Energy in the Earth Systems," scheduled for release in January 1999.
- SAGE is collaborating with other geoscience organizations to support implementation of earth and space science curriculum standards in high schools and to develop an earth systems science core curriculum for higher education non–geology majors.
- The Partners for Education Project now has 1,800 volunteers interacting with science teachers and students from kindergarten to university level, and 600 of these volunteers are on-line as e-mail Partners.
- Plans have been developed for the Colorado Rock Park Project, an outdoor exhibit representing Colorado's geology, geography, and history. The project is expected to be a model for similar educational installations elsewhere in the country.

Institute for Environmental Education (IEE). IEE has successfully promoted the participation of the geoscientific communities in the integration of sound scientific information into policy discussions and decisions.

- IEE initiated and led a series of special-focus workshops to facilitate the transition of the National Biological Service into the USGS/Biological Resources Division.
- A second mentorship program, the Mann Mentorships in Applied Hydrogeology, has been added to the Shlemon Mentors in Applied Geology to encourage dialogue between students and professional geologists from outside academia.
- To facilitate cooperative leadership in integrating the earth, life, and social sciences, IEE partnered with the Ecological Society of America and the USGS to present a specialized workshop, "Enhancing Integrated Science."
- IEE has collaborated with other organizations to present two workshops focusing on predictive modeling for environmental policy making.
- The Congressional Science Fellowship, maintaining an effective voice for the geosciences in Congress, has been increased to an 18-month tenure to increase continuity.
- A new program providing stipends for summer internships at national parks supported two interns in its first year and six interns in its second year; it is set to grow to 10 interns for the summer of 1999.

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Crust *continued from p. 3*

are absent elsewhere. Similarly, evidence for north-south Tertiary shortening is prevalent in the footwall, but absent in the hanging wall. For example, the Cretaceous Schneeberg syncline in the hanging wall is on strike with one of the major Tertiary antiforms in the footwall (Fig. 2B), but was unaffected by formation of the antiform. Alpine-age fabrics are absent in hanging-wall rocks and their Cretaceous mica cooling ages preclude Tertiary heating or penetrative deformation (Frank, 1987).

The upper and lower crust in this region thus responded differently to Tertiary plate convergence. The western Tauern rocks record east-west lower crustal flow and north-south shortening contemporaneous with semipenetrative, mid-crustal, brittle faulting, whereas the overlying Austroalpine rocks underwent only insignificant synchronous deformation (Fig. 2B). A geologist working in the Austroalpine units would infer an episode of north-south contraction associated with moderate heating during the Late Cretaceous, followed by cooling and relative quiescence until the present. In contrast, a geologist working in the western Tauern window would infer extreme east-west stretching and north-south contraction from ~35 Ma until <10 Ma. Both are correct, but each tells only a part of the story.

EXAMPLE 2—SANBAGAWA AND SHIMANTO BELTS, SOUTHWEST JAPAN

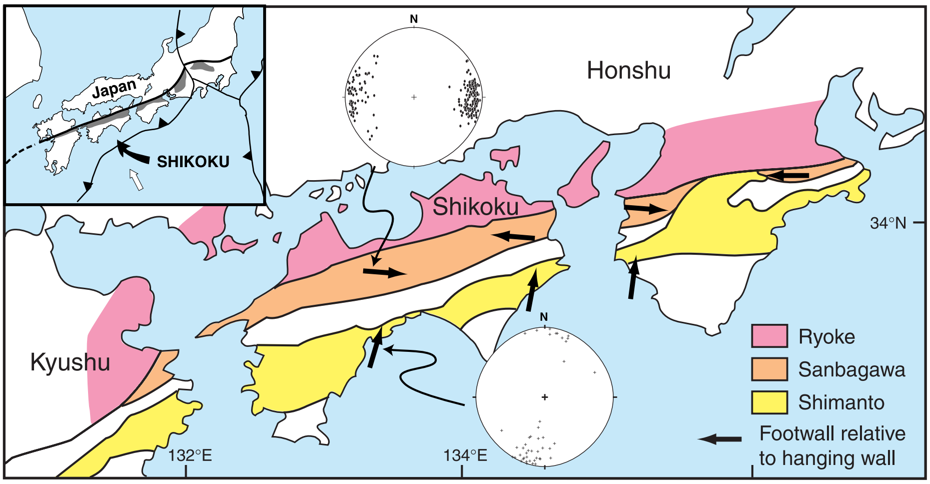

Figure 3. Location map and representative structural data (stretching lineations) from the Sanbagawa and Shimanto belts. Units locally present between these belts (no pattern) represent either transitional packages (e.g., Banno, 1998) or klippe derived from units exposed on Honshu Island (Isozaki and Itaya, 1991; Taira et al., 1992). Arrows show mean trends of lineations and sense of movement of footwall with respect to hanging wall. Shimanto belt records consistent north-directed underthrusting, whereas Sanbagawa belt shows different senses of movement at different structural levels.

High-pressure–low-temperature rocks of the Sanbagawa belt (Fig. 3) form part of a classic "paired metamorphic" belt (Miyashiro, 1961). Recently, the importance of retrograde metamorphism and recrystallization has been emphasized in the region. Wintsch et al. (1999) have suggested that retrograde fabrics formed as the Sanbagawa belt was extruded eastward during Late Cretaceous oblique plate convergence. Thermal and biostratigraphic data suggest that extrusion was driven, at least in part, by underplating of the younger, more seaward Shimanto belt (Kimura, 1997). The kinematic histories of the two belts, however, are strikingly different and suggest substantial crustal-scale heterogeneities in strain (Wintsch et al., 1999).

The Sanbagawa belt forms a generally north-dipping package of regional-scale nappes and folds below the Cretaceous Ryoke magmatic arc and above the accreted rocks of the Cretaceous Shimanto belt (Fig. 3). The belt comprises two tectonostratigraphic units: the Besshi and the Oboke (Takasu and Dallmeyer, 1990). The structurally higher Besshi unit is composed largely of pelitic, mafic and siliceous schists with deep marine protoliths. Peak metamorphic conditions of this unit generally range from epidote-glaucophane to epidote-amphibolite facies (~550 °C and 10 kbar) (Banno, 1986; Miyashiro, 1961), the highest-grade rocks occurring in the core of an east-striking, regional-scale fold (Takasu et al., 1994; Wallis, 1998). The Oboke unit has a distinctly lower metamorphic grade, reaching only pumpellyite-actinolite facies. Wintsch et al. (1999) and Hara et al. (1992) proposed that the Oboke represents a more deformed and deeply buried equivalent to the Shimanto belt.

Support Your Society *continued from p. 3*

Restructuring of GSA Meetings. During the past two years, the Annual Program Committee has initiated numerous enhancements to provide more flexible opportunities and to promote excellence in the scientific presentations at the annual meetings. Some of the changes were introduced in 1998; more will be implemented by 1999; and more still are being planned for the future.

- Pardee keynote symposia, supported with funds from the Joseph T. Pardee bequest, present up to eight leading-edge topics, selected by a review panel, to illustrate the breadth and significance of the geosciences.
- Topical sessions offer up to 70 predetermined topics, combining both invited and volunteered papers.
- Hot topics, expressly chosen for their controversial aspects and impact on the geoscientific community, are noontime debates available to all attendees.
- Technical wizardry has enabled Web-based development of a session proposal system, an abstracts scheduling system, and GeoTimer for on-line abstract and session searches in advance of the meeting.
- To expand national and international perspectives, program chairs for the technical program and hot topic sessions will be chosen through a process of member-wide search and selection.
- The chairs of the Annual Program Committee, the Penrose Conference Committee, and the Continuing Education Committee have met to form a professional development consortium to promote a coordinated approach to program planning for professional geologists.

Internationalization. In an increasingly active effort to facilitate GSA's broader outreach:

- International Secretary Ian Dalziel has met with geoscientists abroad who have confirmed an interest in joint programming.
- GSA has formed a task force on international activities and, for the past two years, has brought representatives of international surveys to the annual meeting.
- In a related initiative, a fund established in memory of Charles Lum Drake will provide grants to young foreign geoscientists to attend geoscientific meetings in the United States, forming a counterpart to the 28th IGC Fund that sends American geoscientists to meetings abroad.
- GSA is supporting the 30th IGC, to be held in Brazil, and more Penrose Conferences are being held outside the United States.

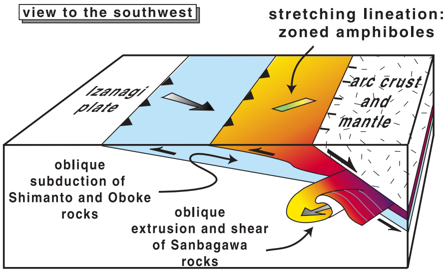

Figure 4. Kinematic interpretation for extrusion and exhumation of the Sanbagawa belt. Movement of the Sanbagawa from west to east (present coordinates), slightly up the dip of the subducting slab to shallower structural levels, is inferred to have been driven by a combination of oblique plate convergence, underplating, tectonic thinning, and partial closure of the subduction channel (see also Wintsch et al., 1999). Regional-scale recumbent fold deforms peak metamorphic isograds and is based, in part, on Wallis (1998).

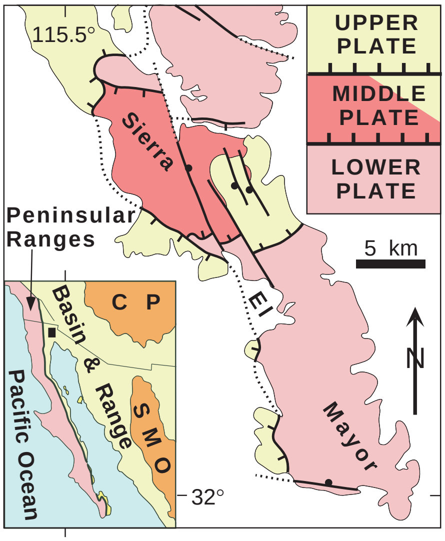

Figure 5. Tectonic map of Sierra El Mayor, Baja California, showing distribution of upper-, middle-, and lower-plate rocks and of late Cenozoic detachment faults (heavy lines with tick marks) that separate them. Yellow is sedimentary strata and red and pink are crystalline basement. Inset of southwestern North America shows location (black square); CP is Colorado Plateau; SMO is Sierra Madre Occidental.

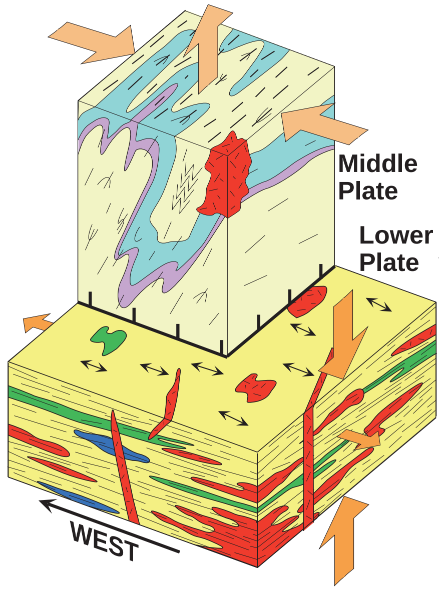

Figure 6. Schematic Cretaceous structures and deformation (orange arrows) of the Sierra El Mayor middle and lower plates, which are now juxtaposed across a younger detachment fault (heavy line with tick marks). Middle plate was thickened vertically and shortened east-west. Lower-plate metamorphic rocks were flattened vertically, which was at least partly offset by vertical inflation owing to sill emplacement, and stretched slightly east-west.

Structural and thermochronologic data from the Sanbagawa belt suggest a progressive 60 m.y. cooling history as it was exhumed and extruded from west to east. High-grade rocks of the Besshi unit cooled through ~500 °C at 94 Ma, through ~350 to 400 °C at 86 to 76 Ma (Takasu and Dallmeyer, 1990), and were at the surface by ~50 Ma, because they are overlain by unmetamorphosed Eocene sedimentary rocks. Whole-rock $^{40}Ar/^{39}Ar$ (Takasu and Dallmeyer, 1990) and zircon fission-track (Shinjoe and Tagami, 1994) ages from the Oboke unit indicate Late Cretaceous cooling. Penetrative, retrograde fabrics, including east-trending stretching lineations, asymmetric shear fabrics, and sheath folds (Faure, 1985; Hara et al., 1977; Hara et al., 1990; Toriumi, 1985; Wallis and Banno, 1990a), document lateral flow, although the dominant flow direction is debated (e.g., Faure, 1985; Hara et al., 1992; Wallis and Banno, 1990b). Top-to-west shear seems to dominate high structural levels, whereas top-to-east shear appears to dominate lower structural levels (Wallis, 1995), suggesting that the middle of the Sanbagawa belt was extruded from west to east (Fig. 4). Extrusion was apparently driven by underplating of rocks represented by the modern Oboke and Shimanto belts.

The Shimanto belt is latest Early Cretaceous to latest Cretaceous in age (Taira, 1985) and was being accreted and metamorphosed as the Sanbagawa belt was cooling and being exhumed (Hasebe et al., 1997; Hasebe et al., 1993; Tagami et al., 1995). The Shimanto belt comprises coherent turbidite sequences and interlayered belts of shale-rich tectonic melange. Metamorphism was relatively low grade, and illite crystallinity, vitrinite reflectance, and zircon fission-track studies document peak metamorphic conditions of ~225 °C (DiTullio and Hada, 1993; Hasebe et al., 1993). Other zircon fission-track data indicate peak metamorphism at about 75 to 60 Ma (Hasebe et al., 1993), similar to K-Ar

Crust *continued on p. 6*

Strategic Long-Term Planning. Over the past two years, a special Committee on Long-Range Planning has developed a series of ambitious strategies to build further on the gains made. Recommendations adopted by Council in October reinforce GSA's commitments

- to our science, expressed in professional meetings and publications and enhanced by extending electronic communications, increasing research and educational grants, and focusing on promoting integrative systems science through collaborations with earth, life, planetary, and social scientists;
- to society, expressed in fostering the education and outreach that bring earth science and its professionals to ever wider, increasingly diverse audiences of students and the general public;
- to our members, by ensuring GSA's vitality and effectiveness as a respected and objective voice on behalf of the geosciences.

As GSA embarked on its second century in 1998, the leadership looked back to assess what GSA had accomplished. The Second Century campaign evolved as the necessary means to augment the programs that defined GSA's proven excellence. At the outset, the goal of $10 million seemed daunting, yet attainment is within reach. We can all be proud not only of the achievement but of the activities that the achievement has made possible.

As we approach the millennium, we now call on the membership to look ahead and to contribute to what GSA will be. The challenges to us, as geoscientists and as members of GSA, have not diminished. But the results of our program initiatives, and of our fund-raising efforts in support of those initiatives, give us the confidence to anticipate that we can meet the challenges.

And with your help, we will. The $9.3 million raised so far is proof that GSA's efforts are worthy of support. I invite all of you to contribute to the efforts. If you have already given, we thank you most sincerely and urge you to renew your gift. If you have not yet made a gift, now is the time when every dollar is a step closer to $10 million—or beyond!

You have recently received a mailing offering you an opportunity to contribute to the success of GSA's Second Century campaign. I hope you will give careful thought to an investment to benefit our Society, our colleagues, and our science.

For further information about how you can make a gift, please contact the GSA Foundation office at 1-800-472-1988, ext. 154. ■

Crust continued from p. 5

ages of cleavage-forming micas (Agar et al., 1989; MacKenzie et al., 1990). Structural and kinematic data from the Shimanto belt, however, indicate north-south shortening or north-directed underthrusting (Byrne and DiTullio, 1992) rather than east-west elongation as in the Sanbagawa belt (Fig. 3). Thus, structural fabrics from these two belts have essentially the same age but preserve very different kinematic axes, suggesting substantial crustal-scale heterogeneities in strain.

EXAMPLE 3—SIERRA EL MAYOR, BAJA CALIFORNIA

The Sierra El Mayor lies in the extended region just east of the stable Peninsular Ranges (Fig. 5; Gastil et al., 1975). Late Cenozoic, brittle, low-angle normal (detachment) faults juxtapose rocks from three different crustal levels (Axen and Fletcher, 1998). The Cretaceous deformation histories of the middle and lower plates are discussed here. The middle plate consists mainly of metasedimentary rocks and various mid-Cretaceous granitic bodies, the lower plate exposes the roots of the plutonic-metamorphic suite (Fig. 1), and the upper plate is made up of Cenozoic sediments.

The metamorphic grade of middle-plate metasedimentary rocks ranges from middle greenschist to lower amphibolite facies (Siem and Gastil, 1994; Axen and Fletcher, 1998); higher-grade rocks are present near granitic intrusions. Compositional layering is isoclinally folded at all scales and overprinted by a penetrative cleavage that is axial planar to north-trending folds (Fig. 6). In pelitic units, euhedral, 1 to 3 mm garnets preserve compositional gradients that probably reflect prograde growth. Granitic bodies are locally present, are unfoliated, and are discordant to country-rock foliation.

The lower plate comprises upper-amphibolite facies migmatitic gneiss (sillimanite + K-feldspar–grade) with subhorizontal flattening foliation (Fig. 6; Axen and Fletcher, 1998). Rare mineral lineations and elongate pressure shadows around garnets trend east-west. Mesoscopic folds are sparse. Granitic units that are broadly coeval with similar units in the middle plate are common and occur as concordant sills, discordant dikes, and centimeter-scale incipient melt segregations parallel to foliation. Garnets in pelitic rocks are typically anhedral, 3 to 15 mm across, strongly embayed by reaction with quartz and biotite, and compositionally homogeneous except for narrow retrograde rims. Bands of hornblende-bearing amphibolite with calc-silicate margins are common.

Preliminary analysis of metamorphic conditions indicates that the detachment fault between the middle and lower plates removed at least 2 km of crust. In particular, andalusite + biotite assemblages in middle plate pelitic rocks indicate peak metamorphic conditions at less than ~10 km depth (Spear, 1993), whereas the disappearance of muscovite and appearance of migmatite in the lower plate suggest the reaction muscovite + plagioclase + quartz = sillimanite + K-feldspar + melt, which takes place above ~3.5 kbar or deeper than ~12 km (Spear and Kohn, 1996). Also, preliminary $^{40}Ar/^{39}Ar$, fission-track, and (U-Th)/He thermochronology of lower-plate rocks (Axen et al., 1998) suggests 5 to 7 km of Neogene tectonic unroofing, which limits horizontal middle-plate translation over the lower plate to <20 km for reasonable fault dips.

Middle-plate structures reflect regional trends, so we are confident that lower-plate structures evolved beneath structures like those in the middle plate. Middle-plate folds probably formed in response to east-west shortening and vertical thickening (Fig. 6) with minor north-south elongation. Although these folds are now largely recumbent, rotation of nonconformably overlying east-dipping sediments back to horizontal brings their axial planes into line with the typical steeply dipping, north-striking folds of the region.

In contrast, lower-plate country rocks record mainly vertical shortening and minor east-west elongation in the absence of noncoaxial shearing (Fig. 6). Where the middle plate is absent and upper-plate sedimentary rocks rest directly above lower-plate gneiss along a brittle detachment fault, the sedimentary rocks generally dip <30° (Siem and Gastil, 1994; Vásquez-Hernández et al., 1996), implying only minor rotation of the fault, its footwall, and the flattening foliation. The high-temperature lower-plate fabrics probably developed in the weak, hot, fluid-like lower part of the middle crust where the rocks could not support differential stress as high as that causing folding in the middle plate. Concordant sills and leucosome (partial melt) were emplaced or generated, respectively, in rocks with anisotropic tensile strength that was greater parallel to foliation than perpendicular to it (e.g., Lucas and St-Onge, 1995). The sills inflated the column vertically, such that the bulk strain ellipse is difficult to characterize.

Existing data are consistent with middle- and lower-plate structures being coeval. For example, regional east-west shortening was common in the Peninsular Ranges during batholith emplacement (e.g., Todd et al., 1988), events we interpret as recorded by middle-plate folds and lower-plate migmatites, respectively. However, better determination of local geochronology is needed.

Thus, broadly coeval principal strain directions in the two levels were very different: middle-plate strain is dominated by east-west shortening, whereas lower-plate strain is dominated by vertical flattening. Middle-plate deformation probably records subhorizontal(?) maximum principal stress of tectonic origin, whereas lower-plate deformation apparently records subvertical maximum principal stress due to lithostatic load at temperatures where much lower differential stress could be maintained.

DISCUSSION, IMPLICATIONS, AND CONCLUSIONS

Our examples illustrate very different, but contemporaneous, principal strains from one crustal level to the next. In the Brenner area in the Alps, the upper crust was essentially rigid, while subjacent levels were extruded laterally with a cigar-shaped bulk strain ellipse imparted in and below a normal shear zone. In southwest Japan, structurally higher but hotter rocks were unroofed and elongated east-west, while cooler, underlying rocks were underplated and shortened north-south. In the Sierra El Mayor in Baja California, mid-crustal rocks were shortened east-west and thickened vertically, while underlying crustal rocks were slightly elongated east-west and shortened vertically at long-term geological rates and incrementally inflated vertically by sill intrusion.

Strain heterogeneity between different crustal levels primarily reflects rheological differences. In the Sierra El Mayor, the lower plate was hotter and weaker than the middle plate, and sill emplacement was controlled by rock strength anisotropy rather than regional stress. In the Alps, the Brenner footwall was weaker than the Austroalpine units due to the combined effects of temperature and rock type. High strains and metamorphic grades, sheath folding, and regionally folded metamorphic isograds in the Sanbagawa belt indicate that it was less rigid than the underlying Shimanto belt. Metamorphic and thermal inversion within the Sanbagawa belt, and between it and the underlying Shimanto belt could be the cause. Fluid released from the subducting Shimanto belt would have also hydrated and weakened the overlying Sanbagawa belt during retrograde conditions.

Thus, flow geometries and strain in weak crustal levels can be largely controlled by complex regional and local boundary conditions. For example, eastward extrusion of the Brenner line footwall is consistent with rigid boundaries to the north, west, and south, and relatively free boundaries above and to the east. Similarly, eastward lateral flow of the Sanbagawa belt during northward underplating of the Shimanto belt could have been directed by the geometry of the overlying, relatively rigid crust and mantle of the arc (Fig. 4).

The heterogeneities we describe comprise *strain partitioning*, which is a natural consequence of acquisition of strain in rocks given their heterogeneous and evolving material properties. Strain partitioning is currently used in at least three ways. The first describes coeval but spatially separate zones of orthogonal simple shear, typically along oblique plate margins where strike-slip faults are separated from genetically related dip-slip faults (e.g., Fitch, 1972; Stock and Hodges, 1989). The second refers to different deformation mechanisms that contribute, coevally or not, to the bulk strain in a rock body (e.g., Ramsay and Huber, 1983). The third involves zones in which strain magnitude is higher than in the surroundings, as in the cores of shear zones (e.g., Mohanty and Ramsay, 1994). None of these usages fits our examples well. To unify these various concepts, we suggest a general definition: *strain partitioning is the natural division of strain into discrete parts in one or more of these mutually compatible ways: (1) kinematic division of strain onto distinct structures, (2) spatial variation of strain orientation and/or magnitude, and (3) distribution of strain among different deformation mechanisms within the same body.* Also, distinguishing between coeval, progressive, and temporally distinct strain partitioning is desirable.

If strong three-dimensional strain heterogeneity is as common as we suggest (existing examples are too numerous to cite), then there are serious implications for characterization of continental crust. For example, various types of vertical profiles are widely used in geophysical and geological studies (e.g., seismic reflection profiles, two-dimensional dynamic and kinematic models, balanced and restored cross sections). These profiles can be very useful in upper crustal studies, where deformation commonly may be adequately characterized in two dimensions, but their construction and interpretation typically hinges on a lack of motions into and out of the profile plane. These two-dimensional analyses will not adequately represent the (typical?) tectonic evolution of regions with strong three-dimensional strain partitioning.

Our examples also show the difficulty inherent in inferring paleo–plate motions from deformed rocks in ancient orogenic belts. The plate tectonic framework of the Brenner area in the Alps is relatively well known from combined seafloor data and the present positions of the continents (e.g., Dewey et al., 1989). However, without this, very different plate kinematic models could result from reconstructions based independently on the Austroalpine vs. the Tauern strain records. In the Japanese and Mexican examples, inferences about ancient plate motions would depend strongly on the level of exposure studied.

Complex vertical strain partitioning could be the norm rather than the exception in geologically complex areas where perturbations of regional and local boundary conditions, heat flow, tectonic and topographic load, and rock strength are complex and evolving. Description and modeling of active and inactive orogenic belts should take into account three-dimensional heterogeneous strain, or have strong reasons for its dismissal, before two-dimensional models are given total credence.

The strain patterns of the weak levels of the present middle to lower crust are particularly poorly known, because of inaccessibility and the weak dependence of most geophysical imaging techniques on strain patterns. Analogy to ancient examples will likely be key to understanding the distribution of heterogeneous deformation in continental crust, and to surficial processes that may affect or be affected by such heterogeneity.

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