PROPOSAL FOR INTERNATIONAL MULTIDISCICPLINARY RESEARCH PROJECT OF THE INTERNATIONAL LITHOSPHERE PROGRAM

ERAS: EARTH ACCRETIONARY SYSTEMS (in space and time), Version 01/12/03

Significance and innovation

Classic models of orogens involve a Wilson cycle of ocean opening and closing with orogenesis related to continent-continent collision. Such models fail to explain the geological history of a significant number of orogenic belts throughout the world in which deformation, metamorphism and crustal growth took place in an environment of ongoing plate convergence. These belts are termed accretionary orogens but have also been refereed to as non-collisional or exterior orogens, Cordilleran-, Pacific-, Miyashiro-, and Turkic-type orogens (Crook, 1974; Kusky et al., 1997a; Maruyama, 1997; Murphy and Nance, 1991; Sengör and Natal'in, 1996; Windley, 1992).

Accretionary orogens have been active throughout Earth history. They constitute major sites of continental growth and mineralization and include Archaean greenstone belts worldwide, Proterozoic orogens (e.g., the Birimian of West Africa, Svecofennian of Finland and Sweden, Cadomian of western Europe, Mazatzal-Yavapai in southwestern USA, and the Arabian-Nubian shield), Neoproterozoic-Palaeozoic orogens in Central Asia (Altaids), as well as Neoproterozoic to Recent orogens of the circum-Pacific and Caribbean. Accretionary orogens form at sites of subduction of oceanic lithosphere. They consist of accretionary wedges containing material accreted from the downgoing plate and eroded from the upper plate, island arcs, ophiolites, oceanic plateaus, old continental blocks, post-accretion granitic rocks and metamorphic products up to the granulite facies, exhumed high-pressure metamorphic rocks, and clastic sedimentary basins. Accretionary orogens contain the bulk of the mineral deposits formed throughout Earth history, and thus provide the mineralisation potential of many countries such as Australia, Canada, Zimbabwe, Saudi Arabia, Yemen, Nigeria, China, Kazakhstan and Mongolia.

Our understanding of the processes for the initiation and development of accretionary orogens is moderately well established in modern orogens such as Japan, Indonesia and Alaska, the broad structure and evolution of which are constrained by seismic profiles, tomography, field mapping, palaeontology and isotope geochemistry and geochronology. However, the processes responsible for the cratonization and incorporation of accretionary orogens into continental nuclei and the mechanisms of formation of pre-Mesozoic accretionary orogens are poorly understood (e.g., Kusky and Polat, 1999). In a uniformitarian sense many of the features of, and processes of, formation of modern accretionary orogens have been little applied to pre-Mesozoic orogens. *Resolution and understanding of these processes form the central aim of this proposal.*

We believe that an integrated, multi-disciplinary and comprehensive program in selected accretionary orogens will provide a common framework to better understand their development. We term this proposal **ERAS** (**E**a**R**th **A**ccretionary **S**ystems in space and time), and the following is intended to provide a basis for discussion and to generate interest in the Earth Science community. Ideas and a detailed work program will be further developed and refined through meetings at international conferences. These will encourage interested scientists to join in developing plans to implement components of the program, which we believe will advance our understanding of accretionary systems in particular and continental evolution in general. The proposal will bring together scientists from many disciplines of the earth sciences.

The common orogenic framework that this project will provide for accretionary belts is seen as a major stimulus for the study of these highly significant orogenic systems. Recognition of the importance of accretionary orogens has been hindered by the lack of a unifying model, with different possible evolutionary paths, to explain their evolution, or recognition of a common suite of processes that operate in many accretionary orogens. Thus, this program has the potential to develop a new conceptual framework (paradigm) for accretionary orogens and to stimulate research in the coming decade not only on orogenesis but on topics ranging from basin analysis and mineralization to mantle flow and its controls on plate tectonics within such systems, just as the models for geosynclines (Aubouin, 1965; Kay, 1951), plate tectonics and mountain belts (Dewey, 1969; Wilson, 1966), terranes (Coney et al., 1980) and supercontinents (Dalziel, 1991; Hoffman, 1991; Moores, 1991) provided a stimulus to orogenic and geological research in past decades.

Orogens in general

Orogens are divisible into two basic types: collisional and accretionary. Plate tectonic models of orogenesis have been dominated by work on collisional orogens with deformation and metamorphism related to ocean closure and subsequent collision of continental blocks to generate mountain belts (Dewey, 1969; Wilson, 1966). This in part reflects the historical influence of European and Eastern North American work on the Appalachian-Caledonian and Alpine-Himalayan systems. However, it has also long been recognized that the Palaeozoic to Recent history of the Circum-Pacific region does not readily fit such a model (Coney, 1973; Crook, 1974; Matsuda and Uyeda, 1971; Packham and Leitch, 1974) and that alternate mechanisms for this type of orogenesis are required.

Accretionary and collisional orogens are the end members of a spectrum of orogens. For example, the collisional western Himalayan orogen contains the accreted Kohistan island arc, the Palaeoproterozoic Trans-Hudson orogen contains the Flin Flon-Snow Lake and La Ronge island arcs, and the Neoprotereozoic to Palaeozoic Altaid accretionary orogen (Sengör et al., 1993) contains a Himalayan-style belt where a continental block has collided with an island arc. The Altaid orogen completed its history with a Himalayan-style collisional orogen in northern China (Xiao et al., in press). Nevertheless, accretionary orogens stand out as an integral, well-defined group of orogens that are further characterized by juvenile crustal growth (Sengör and Natal'in, 1996).

Andean-type accretionary orogens develop where subduction beneath the front of an old continental block has given rise to voluminous calc-alkaline magmatism, and they involve considerable vertical accretion of the crust but relatively little lateral accretion. Andean-type magmatic arcs form commonly during the evolution of collisional orogens like the Himalayas. In accretionary orogens they may form on the margins of accreted continental blocks (Windley et al., 2002), when there is a pause in accretion as on the Ordovician Main Mongolian Lineament in the Altaids, and towards the end of the life of an orogen, against accreted material that had by then consolidated as in Inner Mongolia, China (Xiao et al., in press). One of the first identifiable Andean-type arcs to develop in an accretionary orogen was in the Archaean Minto block of the Canadian Superior Province (Percival et al., 1994). These minor, but important, Andean-type magmatic arcs in accretionary orogens have been little recognized. In this project we plan to make the first detailed geochemical studies of this new type of Andean arc, and make much-needed comparison with the well-documented magmatic arc in the Andes.

Accretionary orogens

Still-evolving accretionary orogens, as around the Pacific, have long, narrow aspect ratios, but completed orogens are typically as broad as long (e.g. Altaids, Arabian-Nubian Shield, and Superior and Yilgarn provinces). They dominantly comprise juvenile mafic to silicic calc-alkaline igneous rocks and their sedimentary products. They are variably deformed and metamorphosed by tectono-thermal events up to granulite- and occasionally to eclogite-facies. Deformational features include structures formed in extensional and compressive environments during steady-state convergence (arc/backarc vs. accretionary prism) that are overprinted by short regional compressive orogenic events (Fig. 1; see review by Kusky and Bradley, 1999).

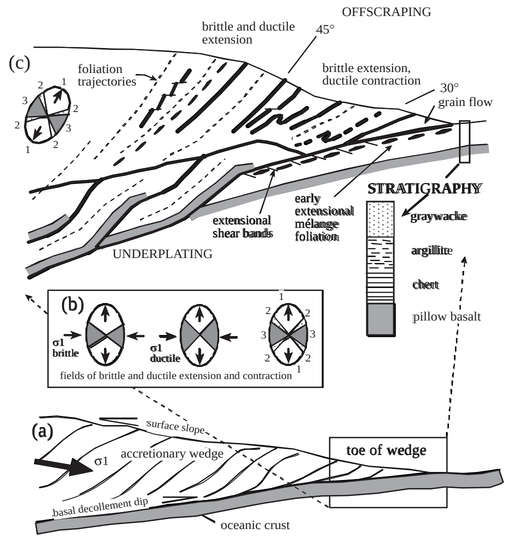

Fig. 1. Complex extensional and contractional structures forming in an accretionary wedge, reflecting kinematics and coupling between upper and lower plates (from Kusky and Bradley, 1999).

Accretionary orogens can be broken into two end-member types (Fig. 2), namely retreating and advancing, based on their contrasting geological character and modern examples from the eastern and western Pacific which reflect a gross long-term kinematic framework with respect to an asthenospheric reference frame. Retreating orogens are undergoing long-term extension in response to a lower plate retreating with respect to the overriding plate, resulting in repeated cycles of forearc accretion that have created the Japanese Islands (Maruyama et al., 1997) and of back arc basin opening as exemplified by the Tertiary history of the western Pacific (Leitch, 1984; Taylor and Karner, 1983). Advancing orogens develop in an environment in which the overriding plate is advancing towards the downgoing plate in an asthenospheric reference frame. For the eastern Pacific this corresponds to westward motion of the North and South American plates. This has resulted in accretion (and strike-slip motion) of previously rifted-off arc and microcontinental ribbons and extensive retro-arc fold and thrust belts.

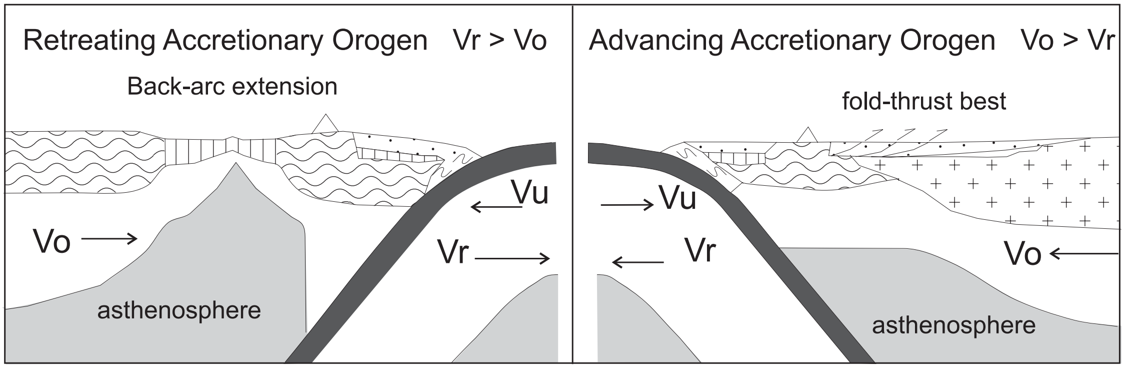

Fig. 2. Accretionary orogen types – for the retreating-type the velocity of slab retreat (Vr) for the underriding plate (Vu) is greater than that of the overriding plate (Vo), whereas for the advancing orogen the velocity of the overriding plate is greater.

Retreating orogens

Japan is the longest-lived and best studied accretionary orogen in the western Pacific (Taira, 2001; Isozaki, 1996; Maruyama et al., 1997), and is the best modern analogue of an accretionary orogen formed largely by rollback-forearc accretion. It is useful to outline the main features of this orogen, because they are key criteria to look for in pre-Mesozoic orogens.

Relicts of the ocean floor are important components of collisional and accretionary orogens, but they are very different in type. The definition of ophiolite stratigraphy (ultramafic rocks, gabbro, sheeted dykes, basalt, sediments) by Anonymous (1972) was based largely on knowledge of ophiolites in the collisional Alpine orogen of Europe, where ophiolites have been obducted onto shelf sediments on continental margins, and at that time there was little or no knowledge or recognition of accretionary orogens. In southern Japan there are over 1000 slices of ocean floor within the accretionary wedges, but they consist of just basalt overlain by ocean floor sediments; the sheeted dykes, gabbros and ultramafic rocks have been subducted. Therefore, when looking at pre-Mesozoic accretionary orogens, we should be looking for the basalt-sediment slices not ophiolites (e.g. Cawood, 1982, 1984). The wrong question is some-times asked ‘where are the ophiolites in the Archaean?’ In the Archaean there were very few continents, therefore few collisional orogens and therefore few ophiolites, but there were abundant accretionary orogens, where we should expect, on uniformitarian arguments, to find just slices of basalt-sediment (e.g. Kusky and Bradley, 1999). This feature of modern accretionary orogens, and its implications, has been largely missed by the ‘Archaean’ geological community, and by those who try to calculate the thickness of the oceanic crust through geological time (e.g. Moores, 1993, 2002).

‘Ocean plate stratigraphy’ consists of the succession ‘MORB-type basalt, chert, hemipelagic mudstone, turbidite or sandstone and conglomerate. It records the history of sedimentation on the ocean floor as it travels from a ridge to a trench. The biostratigraphy, structure, and geochemistry of these offscraped sediments have been much studied in Japan (Isozaki et al., 1990; Matsuda and Isozaki, 1991; Kimura and Hori, 1993; Kato et al., 2002). Because the sediments are very low-grade and well-preserved, the original thrusts were first recognized by micropalaentologists (Matsuda and Isozaki, 1991), not by structural geologists.

Biostratigraphic studies in chert-clastic lithologies in the Franciscan complex of California and in Mexico demonstrated a comparable early accretionary history in the eastern and western Pacific (Sedlock and Isozaki, 1990; Isozaki and Blake, 1994). In Australia Cawood, (1982, 1984) and Cawood and Leitch (1985) recognized an imbricated basalt-chert-siltstone succession consistent with the conveyor belt-type stratigraphy developed on upper oceanic crust as it moves from spreading ridge to subduction zone in the Paleozoic accretionary complex of the Terra Australis orogen, and Ferguson (2003) recorded early Palaeozoic ocean plate stratigraphy in the Lachlan fold belt. In Alaska, Kusky and Bradley (1999) mapped an imbricated oceanic plate stratigraphy where the greywacke-chert-basalt sequence is imbricated many times across a 40 km wide outcrop width of mélange. Kato et al. (1998) and Kato and Nakamura (2003) described chert-clastic sediments in the Archaean Pilbara craton, where trace elements record a remarkably similar ridge-trench transition. In an extensive accretionary orogen, one may expect that rivers would transport to the trench, not continental clastic debris, but mafic debris derived from eroded arcs. The resultant stratigraphy of basalt-chert-mafic sediment was recognized by Komiya et al. (1999) in the 3.8 Ga greenstone belt at Isua, West Greenland, and was recently found for the first time in the 600 Ma Mona Complex of Anglesey, North Wales (Maruyama, Windley, and Watanabe, unpubl. observations). Although other examples of ocean plate stratigraphy are known throughout the geological record, particularly in accretionary orogens, they have been little recognized and poorly studied.

Accretionary wedges are a common ingredient in modern accretionary orogens. The Cretaceous-Tertiary Shimanto accretionary wedge in Japan and the southern Alaskan margin provide the best currently available records of accretionary processes in the circum-Pacific region (Taira et al., 1988; Kusky and Bradley, 1999; Sisson et al., 2003). The Tertiary sediments of Japan have been compared with Recent equivalents in the offshore Nankai Trough to provide a coherent understanding of the structure and evolution of a trench wedge (Pickering and

Taira, 1994). The wedges may contain ocean floor rocks offscraped from the downgoing plate into mélanges, and clastic sediments derived by erosion of continental or arc material and deposited in the trench. Mélanges are of two types (Isozaki, 1997). Chaotic mélanges contain lenses of ultramafic rocks, gabbros, greenschist metabasalts and clastic sediments in a clastic matrix.

It is important to note that mélanges with gabbroic and ultramafic lenses are rare in the accretionary wedges of Japan (Isozaki et al., 1990). Coherent mélanges formed where the first thrusting took place in cold water in the trench parallel to bedding, and gave rise to thrust duplexes in such a way that the thrusts are difficult to determine even at prehnite-pumpellite metamorphic grade, as in the 2-3 m.y. old Miura Group near Tokyo. Similarly, relatively small parts of the southern Alaska accretionary wedge contain chaotic mafic-dominated mélanges or easily recognizable imbricated oceanic plate stratigraphy. Vast stretches of this accretionary wedge, thousands of km long, are dominated by variably-disrupted to coherent greywacke-argillite trench turbidites, with rare ophiolitic slivers and sparse early ridge-subduction related plutons and dykes (Kusky et al., 1997; Kusky and Bradley, 1999; Sisson et al., 2003). The easy-to-recognize chaotic mélanges are known from many parts of the geological record, but the coherent mélanges have not been recognized in most pre-Mesozoic accretionary wedges and greenstone belts, where the greenschist metamorphic grade and associated structures have probably overprinted earlier structures. Therefore, the earliest structures described in the world’s greenstone belts are very likely late overprints (e.g., Kusky and Vearncombe, 1997). This means that those familiar with, for example, Precambrian greenstone belt accretionary orogens should look at the Shimanto wedge or the southern Alaskan margin to help recognize the earliest history.

Preliminary results from the southern Alaska margin have shown that controls on whether chaotic mélange or coherent flysch are accreted at convergent margins may lie in the thickness of the sedimentary pile being subducted on the downgoing plate (Fig. 3). Thinly sedimented plates tend to concentrate shear strain in a thin zone that includes oceanic basement structural highs, whereas thickly sedimented downgoing plates tend to disperse shear strains through a thick stratigraphic section with resulting less obvious deformation (Kusky and Bradley, 1999).

Island arcs in the Western Pacific developed by episodic, non-steady state, stepwise, oceanward growth in retreating accretionary systems, where there is evidence of oceanic subduction and arc growth from 530 Ma to the Present. They built on older oceanic crust or accretionary wedges. The calc-alkaline geochemical products in lavas, volcaniclastics and intrusions are well-documented. Plate coupling within an accretionary convergent zone causes arc migration and changes in geochemistry. Coupling will lead to lithospheric thickening in the overriding plate and changes in arc chemistry with a shift towards adakitic compositions (e.g. Samaniego et al., 2002).

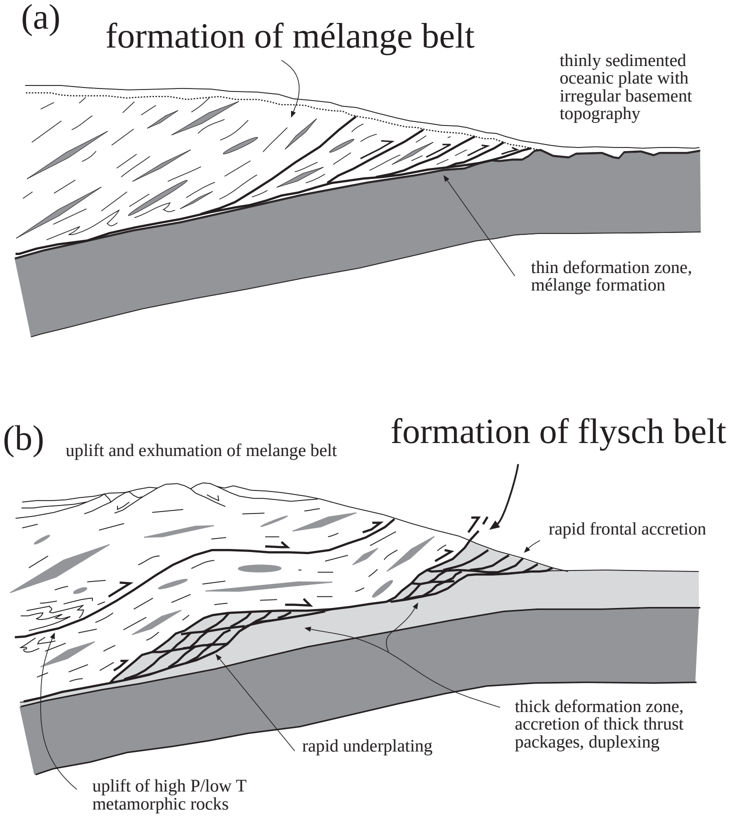

Fig. 3. Model showing possible causes of accretion of flysch and mélange belts in accretionary orogens, depending in part on the thickness of the sedimentary pile on the underriding plate (modified after Kusky et al., 1997b).

In the retreating orogen of Japan many fragments from the Western Pacific ocean collided with, and accreted to, the oceanic margin. For example, there are at least 600 fragments of seamounts with alkali basalts, 26 hot-spot seamounts, 291 oceanic reef limestones, and over 1000 basalt-chert-clastic slices (Isozaki et al., 1990). Many chaotic mélanges with greenstone-limestone lenses were derived from collapse of accreting seamounts (Isozaki, 1997). Many Carboniferous plume-derived hotspot lavas accreted in the latest Permian to middle Jurassic (Tatsumi et al., 2000), and the huge late Jurassic Sorachi oceanic plateau accreted in the early Cretaceous (Kimura et al., 1994). The eclogitic slab on the Sanbagawa mountains was derived from part of an oceanic plateau that was accreted, subducted and exhumed (Maruyama, pers. comm); this shows that the argument of Cloos (1993) that bouyancy would prevent subduction of an oceanic plateau is incorrect. The Izu-Bonin arc has collided with the Honshu arc in the late Cenozoic to give rise to spectacular indentation and curvature of the whole of central Japan (Soh et al., 1998). The above examples demonstrate that accretion and collision of oceanic blocks take place in an accretionary orogen that is ostensibly retreating extensionally towards the ocean.

In the last 450 m.y. in Japan there was an episodic coincident timing of high-P/T nappe exhumation, granite batholith formation, high temperature metamorphism, cooling, uplift, erosion, and clastic sediment deposition. The occurrence of these orogenic culminations approximately every 100 m.y. coincides with the timing of episodic ridge subduction of five major oceanic plates (Isozaki, 1996). Thus, Japan is widely considered to be a ridge subduction-induced, accretionary orogen (Underwood, 1993; Maeda and Kagami, 1996; Osozawa, 1998). The thermal effects of ridge subduction on an accretionary orogen were modelled by Iwamori (2000). In Palaeozoic to Archaean accretionary orogens that have gone to completion, it is difficult to constrain the cause of orogenesis. However, the possibility that ridge subduction may have been a contributing factor has hardly been considered (but see Kusky and Polat, 1999), and yet any other mechanism of orogenesis cannot be fully accepted until ridge subduction is properly evaluated. This proposal will direct attention to this fundamental cause of orogenesis.

Advancing orogens and terrane accretion

Terrane accretion was adopted by Coney et al. (1980) as a new model to explain the formation of the North American Cordilllera, and it is still considered by many to constitute the main (sole) driving force for convergent margin orogenesis in that “eventually a downgoing plate will carry continental or island arc crust into a subduction zone” (Moores and Twiss, 1995, p. 212) to induce arc-arc, arc-continent collision, or terrane accretion (Coney et al., 1980; Dickinson, 1977). Maxson and Tikoff (1996) argued that Cordilleran terrane accretion was the driving mechanism for the Laramide Orogeny. However, in the last twenty years it has become apparent that most, if not all, suspect terrains of the North American Cordillera are upper plate fragments of American affinity (e.g. Johnston, 2001; Monger and Nokleberg, 1996), and recent seismic data across the northern Cordilleran orogen suggest that the accreted terranes are superficial with no deep crustal roots (Snyder et al., 2002). This begs the question: Is terrane accretion an appropriate driving mechanism for orogenesis? Crucial in answering this is determining the exact time of accretion of specific terranes (e.g. Wrangellia) relative to inboard deformation and evaluating the inferred “suspect” character of the terranes. If none of the North American arc fragments are truly exotic, then they all probably formed on the upper plate, and no island arc or continental crust was carried into the subduction zone. Thus, terrane accretion may be an effect of orogenesis not a cause of it: it is an upper plate process that does not involve the transfer of material from the downgoing to the overriding plate. If this analysis is correct, what caused the arcs to collide and terranes to accrete? Also, it should be remembered that, when the idea of terrane accretion was proposed to explain the North American Cordillera the alternative idea of roll-back forearc accretion of a retreating orogen, as in the western Pacific, was not available for consideration. Therefore, the terrane accretion model of orogenesis is ‘suspect’ and requires thorough re-evaluation.

Terrane accretion, in general, may result in chocking of the subduction zone, leading to migration of the magmatic arc and/or a termination of igneous activity, along with a stepping out or flipping of the subduction zone (e.g. Ontong Java Plateau). Flat slab subduction is driven by ridge or plateau subduction. Kay and Mpodozis (2002) argued that the thermal consequences of changing slab dip, combined with subduction of the Juan Fernandez Ridge hot spot track, have left a predictable magmatic and mineralization record in the Andes. Dalziel et al. (2000) suggested that plumes lead to flattening of the downgoing slab, generating "plume-modified orogeny". Flat slab subduction has been invoked as an important mechanism of orogenesis in the accretionary Lachlan orogen (Collins, 2002) and in the North American Cordillera (Saleeby, 2003). The mechanism for increased buoyancy with flat slab subduction depends on the nature and rate of input of the thermal anomaly (Bradley et al., 2003; Kusky et al., 2003). Ridge subduction will be associated with a progressive increase in buoyancy, whereas plateau or hot spot subduction will induce a rapid change in crustal thickness and, hence, buoyancy.

Convergent margin coupling

Potential mechanisms include: (1) subduction of buoyant oceanic lithosphere (flat slab subduction); (2) accretion of buoyant lithosphere (terrane accretion); (3) orogen flexing into continental re-entrant; (4) plate reorganization, causing major changes in convergence direction, including rapid increases in the absolute motion in the overriding plate (Fig. 4); (5) ridge subduction, and (6) steady-state convergence with dewatering of accreted sediments. Each coupling mechanism (outlined below) has predictable consequences for the geological record that this project will evaluate, enabling them to be established or refuted.

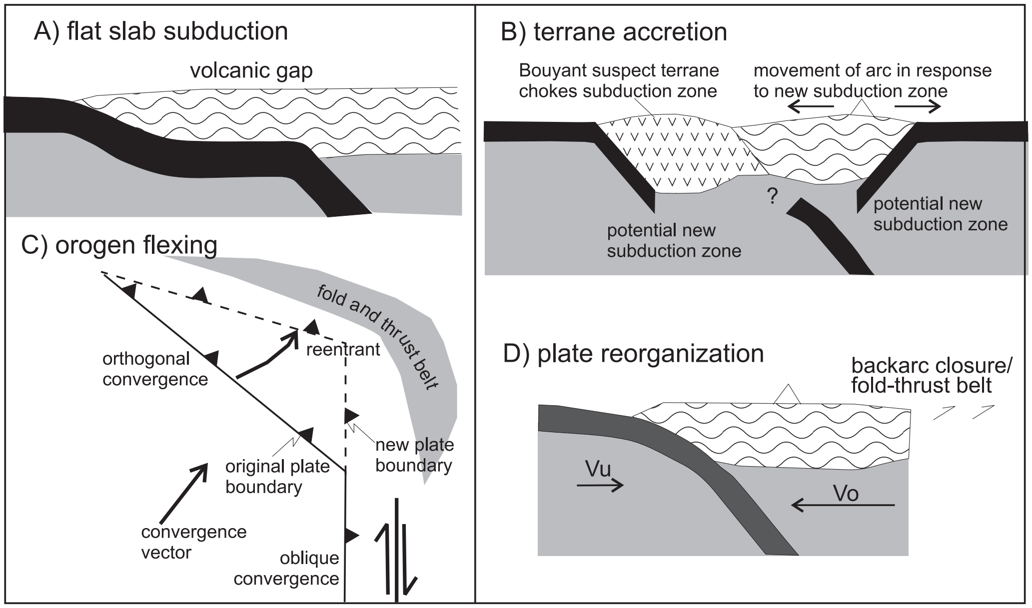

Fig. 4. Modes of plate coupling leading to orogenesis in accretionary orogens.

The effects of (1) flat slab subduction (e.g. Ramos et al., 2002) and (2) suspect terrane accretion should be spatially limited to the region of the flat slab/accretion zone, which should result in short-lived orogenesis and/or diachronous events that migrate along the convergent margin in harmony with the subducted plate movement vector. This will contrast with (4) where the effects of plate reorganisation should be seen synchronously along the orogen/plate boundary and reflect widespread and possibly long-term changes in orogenic character. Plate reorganization may traverse plate boundaries and be inter-orogen in extent. Orogen flexing (3) is associated with convergence of subducted crust into continental recesses and shoaling of the flexed subducted crust. Although the slab flattens where it is flexed, the process is distinguished from flat subduction, which is associated with enhanced slab buoyancy. Examples include the Bolivian and Alaskan oroclines, where the highest compressive stress and highest mountains exist in the North and South American Cordillera (e.g. McQuarrie, 2002). Orogen flexing will show a combination of the above effects: contractional deformation, expressed via developed fold-and-thrust belts should be concentrated near the continental re-entrant, reflecting effects of orthogonal convergence, but may also be a long-term feature. It should leave the diagnostic imprint of a broad oroclinal bend convex toward the craton (i.e. salient). Ridge subduction will be diachronous along strike, and will include structural, magmatic, thermal, and metallogenic fingerprints (Bradley et al., 2003). Steady state convergence with dewatering and deformation of accreted sediments will show kinematics consistent with plate convergence directions and across-strike diachroneity in the time of development of different deformation events. For instance, whereas a newly accreted sediment is growing its first foliation near the trench, a rock that was accreted a few million years earlier may already, and at the same time, be growing its second or third foliation, and associated structures.

Flat slab subduction is taking place today in ten regions worldwide, such as under southern Japan, which thus has a high geothermal gradient not dissimilar from that assumed in Archaean accretionary orogens. Flat slab subduction may be a buoyancy effect related to the impingement of a subducting oceanic plateau, as in the Caribbean and off the Nankai Trough (van Hunen et al., 2002). The buoyancy of a flat slab allows heating and slab melting to give rise to adakitic arc magmas, as in Panama, Costa Rica, Equador, and southern Japan (Gutscher et al., 2000; Samaniego et al., 2000).

Thus, spatial distribution and synchroneity or diachroneity of orogenesis are crucial discriminants of the relevant driving mechanisms. If synchroneity and cyclicity can be established, then the orogenic system may be responding to changes in plate reorganization. If diachroneity can be established, and/or if restricted orogenic events/belts can be identified, more detailed analysis of their kinematic and magmatic character is required to distinguish between the possible, more localized mechanisms, the predicted effects of which are outlined below.

Ridge subduction is a diachronous process that typically involves a major change in plate convergence vectors between the upper plate and two different subducting plates, with the change in plate convergence vectors separated by a period of heating and igneous intrusion in the forearc or in the trench (Fig. 5). Such ridge-trench interaction played a major role in the development of the Tertiary northern North American Cordillera from Kodiak Island, Alaska to Vancouver Island, British Columbia (Sisson et al., 2003). Deformation can be intense and is related not only to the plate convergence vectors (surface forces), but also to a change in dip of the subducting lithosphere as the ridge first approaches the trench and then as the slab window moves away from any point (Kusky et al., 1997a).

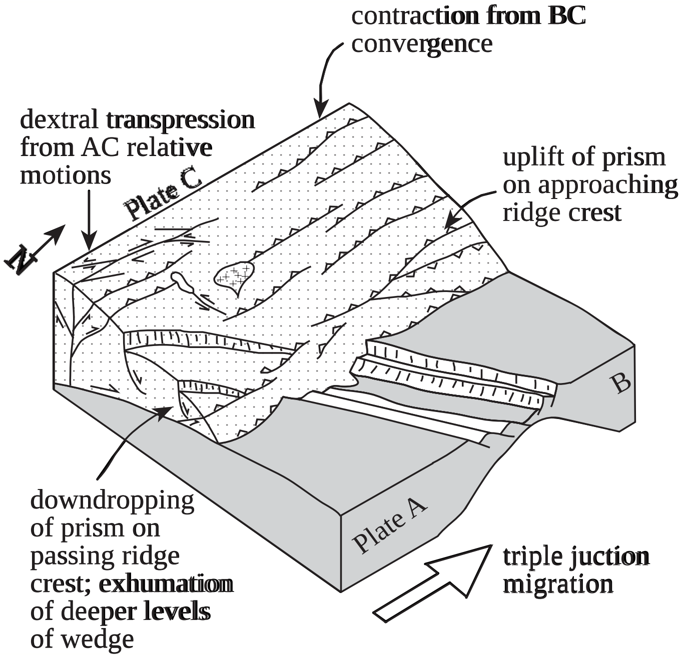

Fig. 5. Oblique view of hypothetical triple junction, showing how structures in upper plate will change with passage of triple junction, reflecting kinematic coupling between plates B and C before ridge subduction, and plates A and C after ridge subduction (from Kusky et al., 1997a).

Crucial in establishing the potential contribution of these different coupling mechanisms to orogenesis is a detailed understanding of the spatial and temporal distribution of the tectonothermal effects of orogenic events in circum-Pacific orogens. Is orogenesis cyclic and/or synchronous on an intra- and inter-orogen scale, reflecting plate reorganization, or is it in intermittent and/or diachronous and limited to an intra-orogen in scale, reflecting local events associated with terrane accretion/flat slab subduction or ridge subduction?

We need to establish the role of transcurrent faulting in the evolution of accretionary orogens. In the case of the North American Cordillera it is very important. Most terranes that have collided, if they have, with western North America in the last 200 m.y. have apparently been fragmented by transcurrent faults and were carried northwards to Alaska, “the great terrane parking lot”. Such fragmentation and lateral transport may also be important in other accretionary orogens and should be investigated by palaeomagnetic and structural methods.

Geochemistry, arc migration and crustal growth

Accretionary orogens have played a major role in crustal growth through Earth history (Kusky and Polat, 1999), whereas crustal growth during collisional orogeny was minor. It will therefore be important to identify which terranes in a given orogen are chiefly juvenile and which are chiefly reworked crust. A combination of Sr, Nd, Hf and Pb isotopic studies, coupled with zircon geochronology, will be important in this part of the investigation. Recently, such studies have been conducted in the Canadian Cordillera and Central Asia (the Altaids), and the results clearly indicate massive addition of juvenile crust during the period of 560 to 100 Ma (e.g., Samson et al., 1989; Kovalenko et al., 1996; Jahn et al., 2000; Wu et al., 2000). We will make the first detailed geochemical studies of Andean-type magmatic arcs in accretionary orogens, and this documentation will establish the compositional variations and characteristics of this newly recognized type of Andean arc.

There is a great diversity of accretionary terranes, many of which are poorly documented, and therefore their nature, composition and evolution require detailed studies. Rock associations are particularly important in characterizing tectonic settings, particularly when coupled with incompatible element distributions and isotopic data. We know very little about the volume of oceanic islands and plateaus that survive in accreted terranes. At present, remnants of only a few oceanic plateaus have been described in accretionary orogens (such as Wrangellia, Sorachi and Sanbagawa). Does this mean that most oceanic plateaus are subducted or have they just not been recognized yet?

Crustal structure in accretionary orogens and mechanism of convergence

Geophysical studies of accretionary orogens have provided fundamental insights into lithospheric structure and processes of accretion and assembly. Seismic (reflection) methods provide relatively high-resolution definition of the geometries of key structures at depth in accretionary orogens. Contrary to geological observations, resolution tends to improve with increasing age of the orogen because greater consolidation of crustal materials with increasing age improves seismic wave propagation. Deep seismic reflection profiles have provided key depth information for a number of Mesozoic to Recent accretionary orogens as well as ones as old as Paleoproterozoic or late Archaean.

LITHOPROBE transects/profiles crossing the Cordillera of Canada reveal the superficial nature of so-called accreted, suspect or exotic terranes (Cook, 1995, Snyder et al., 2002). Most of these terranes are now recognized to: (1) have North American affinity or origin, (2) are 5-15 km thick, and (3) are underlain by a broad, tapering crustal wedge composed of a mixture of crystalline basement rocks and a sedimentary prism deposited onto the passive margin before the accretion orogeny began. The Andes in Peru and Bolivia are not covered by a continuous deep reflection profile, but a number of diverse seismic methods provide depth information within an orogen-spanning transect (Schmitz et al., 1999; Yuan et al., 2000). The path of magma movement from the subducted Nazca oceanic plate to the mid-crust beneath the active volcanic arc is defined by a series of high-amplitude reflections.

Deep seismic reflection profiles across the Banda arc of Indonesia-Australia provide details of crustal structure associated with a subduction polarity flip currently in progress. This orogen differs from the North American Cordillera in that ocean lithosphere attached to the Australian continent was subducted to date, and this continental crust now chokes the subduction zone and causes the subduction flip (Snyder et al. 1996). This is a narrow, very active orogen. High resolution seismic reflection studies have also been undertaken across modern circum-Pacific accretionary orogens (e.g. Hokkaido, northern Japan, Arita et al., 1998), and detailed reconstructions of surface blocks over the past few m.y. have also been proposed for the Indonesian archipelago (for example, Hall, 1997, 2002; Hall and Blundell, 1996).

The relict geometries of Palaeoproterozoic accretionary orogens were defined by the BABEL survey in the Svecofennian domain of NW Europe and by LITHOPROBE in the Hottah terrane of NW Canada (BABEL Working Group, 1993a; Cook et al., 1999) where similar geometries were observed. Fossil subduction zones were recognized in each by clear mantle reflections dipping at about 30 degrees from the Moho to about 100 km depths. The mantle subduction zone nearest the Archaean craton margin is at least 100 km distant from the nearest contiguous Archaean outcrop and indicates that at least 100 km of juvenile crust was thrust or accreted onto the Archaean margin. This process appears to have repeated itself in both examples. The entire Proterozoic terrane was then further thickened and horizontally compacted to produce crustal thicknesses of 37-65 km today.

Seismic reflection, refraction and geoelectric data imply the Svecofennian to be a collage of microcontinental blocks with intervening basins (Korja et al, 1993; Lahtinen et al, in press; Korja and Heikkinen, in press). The reflection seismic data (BABEL, FIRE) revealed well-preserved pre-, syn- to post-collisional structures, e.g. a fossilized arc margin with an attached accretionary prism (BABEL Working Group, 1993a,b), whereas geochemical and petrogenetic studies suggest that the juxtaposed pieces were of Palaeoproterozoic origin. The Svecofennian accretionary orogen could thus be used as an ancient analogue of a future orogen where the Indonesian archipelago with its variable size and age is squeezed between Eurasia and Australia.

In addition to insights derived from deep seismic reflection profiles, seismic refraction profiles have provided details on the crustal structure of accretionary orogens in such diverse settings as Alaska, the southwestern USA, the Arabia-Nubian shield, and the Altaids of central Asia. The Altaids were formed by the coalescence and accretion of diverse crustal fragments during the Palaeozoic and Mesozoic. These crustal fragments include accretionary prisms, island arcs, oceanic crust, and older Precambrian crustal fragments. Seismic refraction data, however, shows that the crust is remarkably uniform in thickness (50 km), with three distinct crustal layers, and a mid-crustal low velocity zone that may have served as a detachment layer during orogenesis (Wang et al., 2003). Significantly, no other evidence has been preserved in the geometry of the deep crustal layers to record the collisional events that built this crust during the Palaeozoic. Instead, crustal layers are nearly flat-lying and rather homogeneous. This uniformity may have been produced by a late Palaeozoic thermal event that caused the crust to undergo partial melting and differentiation. This thermal event is also evidenced by post-collisional granites and calc-alkaline intrusives. This result is in remarkable contrast with seismic reflection data from the Svecofennian craton (BABEL Working Group, 1993a) that shows well-preserved dipping crustal reflections that indicate that geometry of the Precambrian collision process has been preserved.

One major goal of this proposal is the integration of sample-scale data on structural geology, petrology, geochronology and isotopes with both regional-scale lithologic and potential-field data and crustal-scale seismic refraction and reflection as well as geoelectric data in selected accretionary orogens.

A synthesis of orogen-scale seismic reflection data, including the LITHOPROBE results, is currently being prepared as part of IGCP Project 474 "Images of the Earth's Crust – "Inner" Space, the Continents and their Margins". The aim of this project is to make available to a worldwide audience, the best examples of images of the interior of the Earth's crust and upper mantle across a variety of representative structural provinces from all parts of the globe. The first part of their project will concentrate on images from convergent orogens, including accretionary settings. We will collaborate with IGCP 474 through the holding of joint workshops to encourage interaction between the various participants.

Outstanding problems where seismic work may play an important role in the investigation of accretionary orogens include:

Anomalously thick Proterozoic crust. Is this a primary feature of the crust related to exceptionally thick, composite volcanic arcs or oceanic plateau crust? Did it result from a complex accretionary process in which island arcs were folded into oroclines as they entered subduction zones obliquely or where stacked on top of one another? Did later intrusion of more mafic material within the lowermost crust cause the unusual, high seismic wave velocities associated with the lowermost crust in Svecofennia and NW Canada A better understanding of rock assemblages immediately above and below the present-day Moho would help resolve this question of anomalously thick crust and better define what is actually new material accreted to the continent (Durrheim and Mooney, 1994; Hynes and Snyder, 1995).

Mantle anomalies and structures to depths greater than 100 km that are clearly related to accretionary orogens. Such structures are currently partly defined in NW Canada beneath the Hottah and Slave domains (Bostock, 1998), but their better definition and interpretation would be aided by further sudies using multiple seismic techniques as well as electromagnetic (magnetotelluric) surveys.

One observation that has provided evidence on the physical state and tectonic evolution of the lithosphere is the measurement of seismic anisotropy. Such measurements are valuable because they relate to tectonic stress, geotherms, and rheology. Recent measurements (e.g., central Alaska, the Andes, and the Sierra Nevada, California) show that seismic anisotropy is aligned parallel to the structural axis of orogens and has been interpreted to indicate orogen-parallel ductile deformation (i.e., creep) in the uppermost mantle that is a consequence of orogen-perpendicular compressive stresses (Meissner et al., 2002). In order to explain the seismic anisotropy of the mantle beneath young orogens we extend the concept of crustal “escape” tectonics (Molnar and Tapponier, 1975) to the upper mantle. Furthermore, a zone of decoupling is required in the middle or lower crust of orogens in order to explain the observed orogen-parallel mantle anisotropy, but orogen-perpendicular upper crustal anisotropy (Zoback, 1992). Such a decoupling zone is consistent with the observation that accreted terranes are thin (5-15 km) sheets, as noted above.

Palaeomagnetic data have also been important in the study of accretionary orogens. Palaeomagnetism reveals the latitudes and orientations of crustal blocks through time and provides some of the basic quantitative data required for elucidating the tectonic evolution, kinematics, and timing of events within accretionary orogens. For example, palaeomagnetic results from Mesozoic to Cenozoic rocks along the western margin of North America have been interpreted to indicate large-scale northward transport and/or clockwise rotation of ‘displaced’ terranes prior to and during accretion (e.g. Irving, 1979; Coney et al., 1980; Debiche et al., 1987). How the various tectonic units in accretionary belts became assembled and how this assembly occurred can become better understood if the prior spatial distribution of its tectonic elements can be determined. Within limits, palaeomagnetic studies are able to achieve this goal.

Archaean and Palaeoproterozoic accretionary orogens are difficult to study with palaeomagnetism because of their complicated thermo-chemical history that may have erased most of the original magnetic signals. However, younger counterparts of such belts are found in the Neoproterozoic of northeastern Africa/Arabia and in the Palaeozoic Central Asian Orogenic Belt, and these as well as their modern counterparts are eminently suitable for palaeomagnetic studies, particularly since island-arc rocks are typically well suited for such work.

Some models for terrane amalgamation, based at least in part on palaeomagnetism, have been presented by Didenko et al. (1994), Bazhenov et al. (2003), Levashova et al. (2003) and Khain et al. (2003). A successful model for terrane assembly in the Neoproterozoic to late Palaeozoic Ural-Central Asian domain may serve as a useful analog for other pre-Mesozoic accretionary orogens and the amalgamation of supercontinents.

Work program

We propose an integrated, multi-disciplinary and comprehensive program in a spatially and temporally diverse suite of accretionary systems around the Earth. These include: greenstone belts in North America (Superior), Western Australia (Yilgarn), southern Africa (Barberton), Proterozoic orogens (e.g. Birimian of West Africa, Svecofennian of Finland and Sweden, Arabian-Nubian Shield, East African Orogen), Palaeozoic orogens of Asia and Gondwana (Altaids, Terra Australis Orogen, Lachlan Fold Belt), Mesozoic to Recent orogens of the circum Pacific (Japan, Taiwan, Cordillera, Alaska) and the Caribbean.

The Circum-Pacific region provides the outstanding, type examples of accretionary orogens. The Pacific formed during break-up of Rodinia and amalgamation of Gondwana in the

Neoproterozoic and has never subsequently closed, resulting in a series of overall oceanward younging orogenic systems that have always faced an open ocean, yet have been the sites of repeated tectono-thermal events and continental growth. We propose to study Recent to Mesozoic accretionary systems in the Pacific, which provide examples of end-member types of such orogens to resolve and understand their processes of orogenesis. These regions are the most suitable region for these studies because (1) modern examples are evolving within a well constrained kinematic framework; (2) orogenic systems extend back to the Mesozoic and beyond allowing temporal as well as the spatial association of processes to be established; (3) the Pacific shows contrasting end-member accretionary orogen types, allowing potential models for orogenesis in contrasting geologic and kinematic frameworks to be assessed.

Organizational approach

There are many scientists undertaking research in a variety of accretionary orogenic systems around the world. This work is often done in isolation with little reference to those working in other areas and other timeframes. For example, those working in Archaean greenstone belts rarely compare their results with those working in Mesozoic Circum-Pacific orogens. This project will provide a framework for co-operation and sharing of information between workers in spatially and temporally disparate orogens as well as emphasizing a conceptual framework to stimulate new research. Programs such as LITHOPROBE in Canada, ACCRETE in the United States and EUROPROBE in Europe offer possible models for organizing both individuals and institutions in such an ambitious endeavour. The International Lithosphere Program can serve to help organize such activities. Wherever possible, the surveys envisioned here should recognize, build upon and cooperate with ongoing research programs in the areas of interest (e.g., ACCRETE, German Andes project).

We propose that details of geological targeting and geophysical design for this initiative should be formulated in a series of workshops during an initial planning phase. One such workshop is planned in Taiwan for 18-23 May 2004, and further discussions will result from a Session on Accretionary Orogens at the first meeting of the Asia-Oceania Geoscience Society in Singapore in July 2004. We also envisage proposing a Penrose Conference to compare and contrast accretionary orogeny with collisional orogeny. We expect that major field work can take place no earlier than late in 2004, and that a serious program may take anywhere from 5 to 10 years to complete.

References cited

Anonymous, 1972. Penrose field conference report on ophiolites. Geotimes, 17, 24-25.

Arita, K., Ikawa, T., Ito, T., Yamamoto, A., Saito, M., Nishida, Y., Satoh, H., Kimura, G., Watanabe, T., Ikawa, T. and Kuroda, T. 1998. Crustal structure and tectonics of the Hidaka collision zone, Hokkaido (Japan), revealed by vibroseis seismic reflection and gravity surveys. Tectonophysics, 290, 197-210.

Aubouin, J., 1965. Geosynclines. Amsterdam, Elsevier, 335 p.

BABEL Working Group, 1993a. Integrated seismic studies of the Baltic Shield using data in the Gulf of Bothnia region. Geophys. J. Int., 112, 305-324.

BABEL Working Group, 1993b. Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. Geophys. J. Int., 112, 325-343.

Bazhenov, M.L., A.Q. Collins, K.E. Degtyarev, N.M. Levashova, A.V. Mikolaichuk, V.E. Pavlov, and R. Van der Voo, 2003. Paleozoic northward drift of the North Tien Shan (Central Asia) as revealed by Ordovician and Carboniferous paleomagnetism, Tectonophysics, 366, 113-141.

Bostock, M. G., 1998. Seismic stratigraphy and evolution of the Slave province. J. Geophys. Res. 103, 21,183-21,200.

Bradley, D.C., Kusky, T.M., Haeussler, P., Rowley, D.B., Goldfarb, R., and Nelson, S., 2003. Geologic signature of early ridge subduction in the accretionary wedge, forearc basin, and magmatic arc of south-central Alaska. In: Sisson, V.B., Roeske, S., and Pavlis, T.L. (eds.), Geology of a transpressional orogen developed during a ridge-trench interaction along the North Pacific margin. Geol. Soc. America, Spec. Paper in press.

Cawood, P.A., 1982. Structural relations in the subduction complex of the Paleozoic New England Fold Belt, eastern Australia. J. of Geology, 90, 381-392.

Cawood, P.A., 1984. A geochemical study of metabasalts from a subduction complex in eastern Australia. Chemical Geology, 43, 29-47.

Cawood, P.A. and Leitch, E.C., 1985. Accretion and dispersal tectonics of the Southern New England Fold Belt, eastern Australia; in Howell, D.G., ed., Tectonostratigraphic Terranes of the Circum-Pacific region. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 1: Houston, Texas, 481-492.

Cloos, M. 1993. Lithosphere buoyancy and collisional orogenesis: subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. Geol. Soc. Am. Bull., 105, 715-737.

Collins, W.J., 2002. Hot orogens, tectonic switching, and creation of continental crust. Geology, 30, 535-538.

Coney, P.J., 1973. Non-collision tectogenesis in western North America, *in* Tarling, D.H., and Runcorn, S.H., eds., Implications of continental drift to the earth sciences. New York, Academic Press, 713-727.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980. Cordilleran suspect terranes. Nature, 288, 329-333.

Cook, F., 1995. Lithopspheric processes and products in the southern Canadian Cordillera: a LITHOPROBE perspective. Can. J. Earth Sciences, 32, 1803-24.

Cook, F. A., van der Velden, A., Hall, K.W. and Roberts, B.J., 1999. Frozen subduction in Canada's Northwest Territories: LITHOPROBE deep lithospheric reflection profiling of the western Canadian Shield, *Tectonics*, 18,1-24.

Crook, K.A.W., 1974. Cratonisation of West Pacific-type geosynclines. J. Geol., 87, 24-36.

Dalziel, I.W.D., 1991. Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair. Evidence and implications for an Eocambrian supercontinent. Geology, 19, 598-601.

Dalziel, I.W.D., Lawver, L.A., and Murphy, J.B., 2000. Plumes, orogenesis, and supercontinental fragmentation. Earth Planet. Sci. Lett., 178, 1-11.

Debiche, M.G., Cox, A., and Engebretson, D.C., 1987. The motion of allochthonous terranes across the Pacific basin. Geol. Soc. Am. Sp. pap. 207, 49p.

Dewey, J.F., 1969. Evolution of the Appalachian-Caledonian orogen. Nature, 222, 124-129.

Dickinson, W.R., 1977. Tectono-stratigraphic evolution of subduction-controlled sedimentary assemblages, *in* Talwani, M., and Pitman III, W.C., eds., Island arcs, deep-sea trenches and back-arc basins. Maurice Ewing Series, vol. 1, Washington, D.C, American Geophys. Union, 33-40.

Didenko, A.L., A.A. Mossakovsky, D.M. Pechersky, S.V. Ruzhentsev, S.G. Samygin, and T.N. Kheraskova, 1994. Geodynamics of Paleozoic oceans of Central Asia, Geology and Geophysics, 35, 118-145 (in Russian).

Durrheim, R. J., Mooney, W. D., 1994. Evolution of the Precambrian lithosphere; seismological and geochemical constraints. J. Geophys. Res., 99, 15,359-15,374.

Ferguson, C.L., 2003. Ordovician-Silurian accretion tectonics of the Lachlan fold belt, southeastern Australia. Austral. J. Earth Sci., 50, 475-490.

Gutscher, A.-A., Maury, R., Eissen, J.-P. and Bourdon, E. 2000. Can slab melting be caused by flat subduction? Geology, 28, 535-538.

Hall, R., 1997. Cenozoic plate tectonic reconstructions of SE Asia. In: Fraser, A. J., Matthews, S. J., Murphy,R.W. (eds.), Petroleum geology of Southeast Asia. Geol. Soc. London Spec. Publ., 126, 11-23.

Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations: J. Asian Earth Sci., 20, 353-431.

Hall, R., and Blundell, D.J. (eds.), 1996. Tectonic evolution of Southeast Asia. Geol. Soc. London, Special Publication, 106, 566p.

Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwana inside-out? Science 252, 1409-1412.

Hynes, A. and Snyder, D., 1995. Deep-crustal mineral assemblages and potential for crustal rocks below the Moho in the Scottish Caledonides. Geophys. J. Internat., 123, 323–339.

Irving, E., 1979. Paleopoles and paleolatitudes of North America and speculations about displaced terrains. Can. J. Earth Sci., 16, 669-694.

Isozaki, Y., 1996. Anatomy and genesis of a subduction-related orogen: a new view of geotectonic subdivision and evolution of the Japanese Islands. The Island Arc, 5, 289-320.

Isozaki, Y. 1997. Jurassic accretion tectonics of Japan. The Island Arc, 6, 25-51.

Isozaki, Y. and Blake, M.C., 1994. Biostratigraphic constraints on formation and timing of accretion in a subduction complex. An example from the Franciscan complex in northern California. J. Geol., 102, 283-296.

Isozaki, Y., Maruyama, S. and Furuoka, F. 1990. Accreted oceanic materials in Japan. Tectonophysics, 181, 179-205.

Iwamori, H. 2000. Thermal effects of ridge subduction and its implications for the origin of granitic batholith and paired metamorphic belts. Earth Planet. Sci. Lett., 181, 131-144.

Jahn, B.M., Wu, F.Y. and Chen, B., 2000. Granitoids of the Central Asian orogenic belt and continental growth in the Phanerozoic. Trans. Royal Society of Edinburgh, Earth Sci., 91, 181-193.

Johnston, S.T., 2001. The Great Alaskan terrane wreck: reconciliation of paleomagnetic and geological data in the northern Cordillera. Earth Planet. Sci. Lett., 193, 259-272.

Kato, Y. and Nakamura, K. 2003. Origin and global tectonic significance of Early Archaean cherts from the Marble Bar greenstone belt, Pilbara craton, Western Australia. Precambrian. Res., 125, 191-293.

Kato, Y., Ohta, I., Tsunematsu, T., Watanabe, Y., Isozaki, Y., Maruyama, S. and Imai, N. 1998. Rare earth element variations in mid-Archean banded iron formations: implications for the chemistry of ocean and continent and plate tectonics. Geochim. Cosmochim. Acta, 62, 3475-3497.

Kato, Y., Nakao, K. and Isozaki, Y. 2002. Geochemistry of late Permian to early Triassic pelagic cherts from southwest Japan: implications for an oceanic redox change. Chem. Geol. 182, 15-34.

Kay, M., 1951. North American Geosynclines. Geol. Soc. America, Mem. 48, 143 p.

Kay, S.M., and Mpodozis, C., 2002. Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab. J. South American Earth Sci., 15, 39-57.

Khain, E.V., Bibikova, E.V., Salnikova, E.B., Kröner, A., Gibsher, A.S., Didenko, A.N., Degtyarev, K.G., and Fedotova, A.A., 2003. The Palaeo-Asian ocean in the Neoproterozoic and early Palaeozoic: New geochronologic data and palaeotectonic reconstructions. Precambrian Res., 122, 329-358.

Kimura, K. and Hori, R. 1993. Offscraping accretion of Jurassic chert-clastic complexes in the Mino-Tamba belt, central Japan. J. Struct. Geol., 15, 145-161.

Kimura, G., Sakakibara, M. and Okamura, M. 1994. Plumes in central Panthalassa? Deductions from accreted oceanic fragments in Japan. Tectonics, 13, 905-916.

Komiya, T., Maruyama, S., Masuda, T., Nohda, S., Hayashi, M. and Okamoto, K. 1999. Plate tectonics at 3.8-3.7 Ga: field evidence from the Isua accretionary complex, Southern West Greenland. J. Geol., 107, 515-554.

Korja, A., Korja, T., Luosto, U., Heikkinen. P., 1993. Seismic and geoelectric evidence for collisional and extensional events in the Fennoscandian Shield – implications for Precambrian crustal evolution. Tectonophysics, 219, 129–152.

Korja, A. and Heikkinen, P., in press. The Accretionary Svecofennian Orogen - Insight from the BABEL profiles. Precambrian Research,

Kovalenko, V.I., Yarmolyuk, V.V., Kovach, V.P., Kotov, A.B., Kozakov, I.K. and Salnikova, E.B., 1996. Sources of Phanerozoic granitoids in Central Asia: Sm-Nd isotope data. Geochemical International, 34, 628-640.

Kusky, T.M. and Vearncombe, J., 1997. Structure of Archean greenstone belts. In: de Wit, M.J. and Ashwal, L.D. (eds.), Tectonic evolution of greenstone belts. Oxford Monograph on Geology and Geophysics, pp. 95-128.

Kusky, T.M., and Polat, A., 1999. Growth of granite-greenstone terranes at convergent margins, and stabilization of Archean cratons. Tectonophysics, 305, 43-73.

Kusky, T.M., and Bradley, D.C., 1999. Kinematics of mélange fabrics: Examples and applications from the McHugh Complex, Kenai Peninsula, Alaska. J. Struct. Geol., 21, 1773-1796.

Kusky, T.M., Bradley, D.C., and Haeussler, P., 1997a. Progressive deformation of the Chugach accretionary complex, Alaska, during a Paleogene ridge-trench encounter. J. Struct. Geol., 19, 139-157.

Kusky, T.M., Bradley, D.C., Haeussler, P., and Karl, S., 1997b. Controls on accretion of flysch and mélange belts at convergent margins: Evidence from Chugach Bay thrust and Iceworm Melange, Chugach Terrane, Alaska. Tectonics, 16, 855-878.

Kusky, T.M., Bradley, D.C., Donley, D.T., Rowley, D. and Haeussler, P., 2003. Controls on intrusion of near-trench magmas of the Sanak-Baranof belt, Alaska, during Paleogene ridge subduction, and consequences for forearc evolution. In: Sisson, V.B., Roeske, S. and Pavlis, T.L. (eds.), Geology of a transpressional orogen developed during a ridge-trench interaction along the North Pacific margin. Geol. Soc. America, Spec. Paper 371, 269-292.

Lahtinen, R., Korja, A. and Nironen, M., in press. Paleoproterozoic tectonic evolution of the Fennoscandian Shield. In. Lehtinen, M., Nurmi, P. and Rämö, T. (eds.) The Precambrian Bedrock of Finland - Key to the evolution of the Fennoscandian Shield. Elsevier Science B.V., in press.

Leitch, E.C., 1984, Marginal basins of the SW Pacific and the preservation and recognition of their ancienct analogues: a review. In: Kokelaar, B.P. and Howells, M.F. (eds.), Marginal basin geology: Geol. Society London, Special Publ., 16, 97-108.

Levashova, N.M., Degtyarev, K.E., Bazhenov, M.L., Collins, A.Q., and Van der Voo, R., 2003. Middle Paleozoic paleomagnetism of east Kazakhstan: post-middle Devonian rotations in a large-scale orocline in the central Ural-Mongol belt, Tectonophysics, in press.

Maeda, J. and Kagami, H. 1996. Interaction of a spreading ridge an accretionary prism: implications from MORB magmatism in the Hidaka magmatic zone, Hokkaido, Japan. Geology, 24, 31-34.

Maruyama, S. 1997. Pacific-type orogeny revisited: Miyashiro-type orogeny proposed. The Island Arc, 6, 91-120.

Maruyama, S., Isozaki, Y., Kimura, G. and Terabayashi, M. 1997. Paleogeographic maps of the Japanese Islands: plate tectonic synthesis from 750 Ma to the present. The Island Arc, 6, 121-142.

Matsuda, T., and Uyeda, S., 1971. On the Pacific-type orogeny and its model: extension of the paired belts concept and possible origin of marginal seas: Tectonophysics, 11, 5-27.

Matsuda, T. and Isozaki, Y. 1991. Well-documented travel history of Mesozoic pelagic chert in Japan: from remote ocean to subduction zone. Tectonics, 10, 475-499.

Maxson, J., and Tikoff, B., 1996. Hit-and-run collisional model for the Laramide orogeny, western United States. Geology, 24, 968-972.

McQuarrie, N., 2002. Initial plate geometry, shortening variations, and evolution of the Bolivian orocline. Geology, 30, 867-870.

Meissner, R., Mooney, W.D. and Artemieva, I., 2002. Seismic anisotropy and mantle creep in young orogens. Geophys. J. Int., 149, 1-14.

Molnar, P. and Tapponier, 1975. Cenozoic tectonics of Asia: effects of continental collision. Science, 189, 144-154.

Monger, J., and Nokleberg, W.H., 1996. Evolution of the northern North America Cordillera: generation, fragmentation, displacement and accretion of successive North American plate margin arcs, *in*: Geology and ore deposits of the American Cordillera. Geol. Soc. Nevada, 1133-1152.

Moores, E.M., 1991, Southwest U.S.-East Antarctica (SWEAT) connection: A hypothesis: Geology, 19, 425-428.

Moores, E.M., 1993. Neoproterozoic oceanic crustal thinning, emergence of continents, and origin of the Phanerozoic ecosystem: a model. Geology, 21, 5-8.

Moores, E.M. 2002. Pre-1 Ga (pre-Rodinian) ophiolites: their tectonic and environmental implications. Geol. Soc. America Bull., 114, 80-95.

Moores, E.M., and Twiss, R.J., 1995. Tectonics. New York, W.H. Freeman and Company, 415 p.

Murphy, J.B., and Nance, R.D., 1991. Supercontinent model for the contrasting character of late Proterozoic orogenic belts. Geology, 19, 469-472.

Opdyke, N.D. and Channel, J.E.T., 1996. Magnetic stratigraphy. Academic Press, San Diego, 346p.

Osozawa, S. 1998. Ridge subduction-induced orogeny, a case study of the Cretaceous to Paleogene in southwest Japan. In Mantle Dynamics and Plate Interactions in East Asia, Amer. Geophys. Union, Geodynamics Series 27, 331-336.

Packham, G.H., and Leitch, E.C., 1974, The role of plate tectonic theory in the interpretation of the Tasman Orogenic Zone. In: Denmead, A.K., Tweedale, G.W., and Wilson, A., F., (eds.), The Tasman Geosyncline - A Symposium. Brisbane, Geol. Soc. Australia, 129-154.

Percival, J.A., Stern, R.A., Skulski, T., Card, K.D., Mortensen, J.K. and Bégin, N.J. 1994. Minto block, Superior Province: missing link in deciphering assembly of the craton at 2.7 Ga. Geology, 22, 839-842.

Pickering, K.T. and Taira, A. 1994. Tectono-sedimentation: with examples from the Tertiary-Recent of southeast Japan. In: Continental Deformation, ed. P.L. Hancock, Pergamon Press, Oxford, pp. 320-354.

Ramos, V.A., Cristallini, E.O., and Perez, D.J., 2002, The Pampean flat-slab of the Central Andes: J. South American Earth Sci., 15, 59-78.

Saleeby, J., 2003. Segmentation of the Laramide Slab-evidence from the southern Sierra Nevada region. Geol. Soc. America Bull., 115, 655-668.

Samaniego, P., Martin, H., Robin, C., and Monzier, M., 2002. Transition from calc-alkalic to adakitic magmatism at Cayambe volcano, Ecuador: Insights into slab melts and mantle wedge interactions. Geology, 30, 967-970.

Samson, S.D., McClelland, W.C., Patchett, P.J., Gehrels, G.E. and Anderson, R.G., 1989. Evidence from neodymium isotopes for mantle contributions to Phanerozoic crustal genesis in the Canadian Cordillera. Nature, 337, 705-709.

Schmitz, M, Lessel, K, Giese, P, Wigger, P, Araneda, M, Bribach, J, Graeber, F, Grunewald, S, Haberland, C, Lueth, S, Roewer, P, Ryberg, T, Schulze, A, 1999. The crustal structure beneath the Central Andean forearc and magmatic arc as derived from seismic studies; the PISCO 94 experiment in northern Chile (21 degrees -23 degrees S). J. South American Earth Sci., 12, 237-260.

Sedlock, R.L. and Isozaki, Y. 1990. Lithology and biostratigraphy of Franciscan-like chert and associated rocks in west-central Baja California, Mexico. Geol. Soc. Am. Bull., 102, 852-864.

Sengör, A.M.C., Natal’in, B.A. and Burtman, V.S. 1993. Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia. Nature, 364, 299-307.

Sengör, A.M.C., and Natal'in, B.A., 1996. Turkic-type orogeny and its role in the making of the continental crust. Ann. Rev. Earth Planet. Sci., 24, 263-337.

Sisson, V.B., Roeske, S., and Pavlis, T.L., eds., 2003. Geology of a transpressional orogen developed during ridge-trench interaction along the North Pacific margin.. Geol. Soc. America, Spec. Paper 371.

Snyder, D. B., Prasetyo, H., Blundell, D.J., Pigram, C.J., Barber, A.J., Richardson, A. and Tjokosaproetro, S., 1996. A dual doubly vergent orogen in the Banda Arc continent-arc collision zone as observed on deep seismic reflection profiles. Tectonics, 15, 34–53.

Snyder, D.B., Clowes, R.M., Cook, F.A., Erdmer, P., Evenchich, C.A., van der Velden, A.J., and Hall, K.W., 2002. Proterozoic Prism Arrests Suspect Terranes: Insights into the Ancient Cordilleran Margin from Seismic Reflection Data: GSA Today, 12, 4-9.

Soh, W., Nakayama, K. and Kimura, T. 1998. Arc-arc collision in the Izu collision zone, central Japan, deduced from the Ashigara basin and adjacent Tanzawa mountains. The Island Arc, 7, 330-341.

Taira, A. 2001. Tectonic evolution of the Japanese island arc system. Ann. Rev. Earth Planet. Sci., 29, 109-134.

Taira, A., Katto, J., Tashiro, M., Okamura, M. and Kodama, K. 1988. The Shimanto belt in Shikoku, Japan – evolution of Cretaceous to Miocene accretionary prism. Modern Geology, 12, 5-46.

Tatsumi, Y., Kani, T., Ishizuka, H., Maruyama, S. and Nishimura, Y. 2000. Activation of Pacific mantle plumes during the Carboniferous: evidence from accretionary complexes in southwest Japan. Geology, 28, 580-582.

Taylor, B., and Karner, G.D., 1983. On the evolution of marginal basins: Rev. Geophys. Space Phys., 21, 1727-1741.

Underwood, M.B. (ed.) 1993. Thermal evolution of the Tertiary Shimanto belt, southwest Japan: an example of ridge-trench interaction. Geol. Soc. America Spec. Paper 273, 172 p.

Van Hunen, J., van der Berg, A.P. and Vlaar, N.J. 2002. On the role of subducting oceanic plateaus in the development of shallow flat subduction. Tectonophysics, 352, 317-333.

Wang, Y.-X., Mooney, W.D. Yuan, X.-C. and Coleman, R.G., 2003. The crustal structure from the Altai Mountains to the Altyn Tagh fault, northwest China. J. Geophys. Res., DOI:10.1029/2001JB000552.

Wilson, J.T., 1966. Did the Atlantic close and then re-open? Nature, 211, 676-681.

Windley, B.F., 1992. Proterozoic collisional and accretionary orogens, *in* Condie, K.C., ed., Proterozoic crustal evolution. Developments in Precambrian Geology, vol. 10. Amsterdam, Elsevier, 419-446.

Windley, B.F. Kröner, A., Guo, J-H., Qu, G., Li, Y. and Zhang, C. 2002. Neoproterozoic to Palaeozoic geology of the Altai orogen, Chinese Central Asia: new zircon age data and tectonic evolution. J. Geol., 110, 719-739.

Wu, F.Y., Jahn, B.M., Wilde, S. and Sun, D.Y., 2000. Phanerozoic crustal growth: U-Pb and Sr-Nd isotopic evidence from the granites in northeastern China. Tectonophysics, 328, 89-113.

Xiao, W., Windley, B.F., Hao, J. and Zhai, M., in press. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: termination of the Central Asian Orogenic Belt. Tectonics,

Yuan, X., Sobolev, S.V., Kind, R., Oncken, O., Bock, G., Asch, G., Schurr, B., Graeber, F., Rudloff, A., Hanka, W., Wylegalla, K., Tibi, R., Haberland, C., Rietbrock, A., Giese, P., Wigger, P., Rower, P., Zandt, G., Beck, S., Wallace, T., Pardo, M. and Comte, D., 2000. Subduction and collision processes in the Central Andes constrained by converted seismic phases. Nature, 408, 958-961.

Zoback, M.L., 1992. First and second-order patterns of stress in the lithosphere: the world stress map project. J. Geophys. Res., 97, 11,703-11,727.

For more information contact one of the following:

Peter Cawood, Univ. Western Australia, Perth, e-mail: pcawood@tsrc.uwa.edu.au
Alfred Kröner, Mainz University, Germany, e-mail: kroener@mail.uni-mainz.de
Brian Windley, University of Leicester, UK, e-mail: brian.windley@virgin.net
Tim Kusky, Washington University, St. Louis, USA, e-mail: kusky@eas.slu.edu
Walter Mooney, USGS, Menlo Park, USA, e-mail: mooney@usgs.gov
Bor-ming Jahn, National University of Taiwan, Taipeh (jahn@ccms.ntu.edu.tw)

Potential funding

National funding agencies in North America, Europe, Australia, Japan and Asia
European Funding Agencies such as EU, ESF
World Bank (for instruments to be donated to developing countries, plus costs of training indigenous personnel in its use.
UNESCO-training funds
Mining and exploration companies (?)- support could be in kind with use of drill rigs and vehicles in countries of interest
Oil companies, especially those with interests in regions such as the Cordillera fold and thrust belt, Southeast Asia, Caribbean.

Contact list

Australia:	Peter Cawood, Tectonics Special Research Centre, University of Western Australia, Perth, Australia (pcawood@tsrc.uwa.edu.au)
	Bill Collins, University of Newcastle, NSW (Bill.Collins@newcastle.edu.au)
	Tony Crawford, University of Tasmania (tony.crawford@utas.edu.au)
	Barry Drummond, Geoscience Australia (Barry.Drummond@agso.gov.au)
	Chris Fergusson, University of Wollongong (cferguss@uow.edu.au)
	Russell Korsch, Geoscience Australia, (Russell.korsch@ga.gov.au)
	Gordon Lister, ANU, Canberra (Gordon.Lister@anu.edu.au)
Austria:	Franz Neubauer, Salzburg University (franz.neubauer@sbg.ac.at)
Argentina:	Victor Ramos (andes@gl.fcen.uba.ar)
	Carlos Rapella (crapela@way.com.ar)
Brazil	Umberto Cordani (ucordani@usp.br)
Canada:	David Snyder (dsnyder@X1.nrcan.gc.ca)
	Stephen Johnston (stj@uvic.ca)
	John Percival, Ottawa (jpercival@gsc.emr.ca)
	Ali Polat, University of Windsor (polat@uwindsor.ca)
	Cees van Staal (cvanstaa@NRCan.gc.ca)
Czech Rep.:	Karel Schulmann, Charles University, Prague (schulman@mail.natur.cuni.cz)
Finland:	Raimo Lahtinen, Geological Survey, Espoo (raimo.lahtinen@gsf.fi)

France: Alexandre Chemenda, University of Nice (chemenda@geoazur.unice.fr)
Germany: Alfred Kröner, Mainz University (kroener@mail.uni-mainz.de)
Bernhard Stöckhert, Bochum University (bernhard.stoeckhert@ruhr-uni-bochum.de)
Jan Behrmann, Freiburg Uni. (jan.behrmann@geologie.uni-freiburg.de)
Onno Oncken, GFZ Potsdam (oncken@gfz-potsdam.de)
Great Britain: Brian F. Windley, Leicester University (brian.windley@btopenworld.com)
Robert Hall, University of London (robert.hall@gl.rhul.ac.uk)
Japan: Shigenori Maruyama, Tokyo Institute of Technology (s.maruyam@geo.titech.ac.jp)
Yukio Isozaki, Tokyo University (isozaki@chianti.c.u-tokyo.ac.jp)
Russia: Mikhail Buslov, Russian Academy of Sciences, Siberian Branch, Novosibirsk (misha@(uiggm.nsc.ru)
South Africa: Maarten De Wit, Cape Town University (maarten@cigc.uct.ac.za)
Switzerland: Jean-Pierre Burg, ETH Zurich (jpb@erdw.ethz.ch)
Taiwan: Bor-ming Jahn, National University of Taiwan (jahn@ccms.ntu.edu.tw)
USA: Walter Mooney, USGS, Menlo Park, e-mail: mooney@usgs.gov
Tim Kusky, St. Louis University, MO (kusky@eas.slu.edu)
R.J. Stern, U. of Texas at Dallas, Richardson, TX (rjstern@utdallas.edu)
Kent Condie, New Mexico Tech, Socorro, NM (kcondie@nmt.edu)
Rob Van der Voo, Univ. Michigan, MI (voo@umich.edu)
Larry Brown, Cornell University, NY (brown@geology.cornell.edu)
Lincoln S. Hollister, Princeton University (linc@princeton.edu)
Dwight Bradley, USGS, Anchorage, AK ((dbradley@usgs.gov)