Orogenic Belts and Orogenic Sediment Provenance

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ABSTRACT

By selecting a limited number of variables (westward vs. eastward subduction polarity; oceanic vs. continental origin of downgoing and overriding plates), we identify eight end-member scenarios of plate convergence and orogeny. These are characterized by five different types of composite orogenic prisms uplifted above subduction zones to become sources of terrigenous sediments (Indo-Burman-type subduction complexes, Apennine-type thin-skinned orogens, Oman-type obduction orogens, Andean-type cordilleras, and Alpine-type collision orogens). Each type of composite orogen is envisaged here as the tectonic assembly of subparallel geological domains consisting of genetically associated rock complexes. Five types of such elongated orogenic domains are identified as the primary building blocks of composite orogens: magmatic arcs, obducted or accreted ophiolites, neometamorphic axial belts, accreted paleomargin remnants, and accreted orogenic clastic wedges. Detailed provenance studies on modern convergent-margin settings from the Mediterranean Sea to the Indian Ocean show that erosion of each single orogenic domain produces peculiar detrital modes, heavy-mineral assemblages, and unroofing trends that can be predicted and modeled. Five corresponding primary types of sediment provenances (magmatic arc, ophiolite, axial belt, continental block, and clastic wedge provenances) are thus identified, which reproduce, redefine, or integrate provenance types and variants originally recognized by W. R. Dickinson and C. A. Suczek in 1979. These five primary provenances may be variously recombined in order to describe the full complexities of mixed detrital signatures produced by erosion of different types of composite orogenic prisms. Our provenance model represents a flexible and valuable conceptual tool to predict the evolutionary trends of detrital modes and heavy-mineral assemblages produced by uplift and progressive erosional unroofing of various types of orogenic belts and to interpret petrofacies from arc-related, foreland-basin, foredeep, and remnant-ocean clastic wedges.

Introduction

The overall geometry of orogenic belts produced by subduction ... is fundamental for provenance analysis on a global scale. (Dickinson 1988, p. 18)

Orogens are stacks of rock units uplifted above subduction zones by tectonic and magmatic processes, which are influenced by subduction geometry as well as the nature and geological history of converging plates. Although distinct types of orogenic prisms may be identified, natural processes are so varied and complex that any attempt to classify orogenic belts sounds like a hopeless challenge; each mountain chain has its own peculiarities and stands as a case apart.

As a consequence, modeling the provenance of orogenic sediments and sedimentary rocks is an arduous task, and a systematic quantitative treatment of orogenic sediment provenance is lacking. Classic provenance models have dealt with this intricate problem in only a general way, loosely discriminating among three distinct types of orogenic settings (subduction complex, collision-orogen/suture belt, and foreland fold-thrust belt) and three corresponding types of “recycled orogen provenances” (Dickinson and Suczek 1979; Dickinson 1985).

This article focuses on topographically elevated sources of detritus found within thrust belts and arc-trench systems (rather than on the associated basins representing sediment sinks; Dickinson
and proposes a simplified classification of orogenic domains that is intended to represent a useful reference model for a better description and understanding of orogenic sediment provenance.

**Subduction Polarities and Orogen Types**

Current circum-Pacific arcs include east-facing island arcs and west-facing continental arcs in a consistent pattern that implies net westward drift of continental lithosphere with respect to underlying asthenosphere. (Dickinson 1978, p. 1)

Two opposite subduction polarities have long been recognized (Nelson and Temple 1972; Uyeda and Kanamori 1979). Whereas back-arc spreading is characteristic of east-facing arc-trench systems (westward subduction), back-arc thrusting is most widespread in west-facing arc-trench systems (eastward subduction; Dickinson 1978).

Such contrast has often been ascribed to the age of subducting oceanic lithosphere, with older lithosphere being denser and consequently prone to generate a more efficient slab pull (Royden 1993). Systematic analysis of subduction dip and convergence rate at the trench, however, fails to show any significant correlation between age of downgoing lithosphere and slab inclination (Cruciani et al. 2005).

Global tectonics is considered here as fundamentally controlled by Earth’s rotation, with lithospheric plates drifting westward with respect to the mantle (Bostrom 1971; Dickinson 1978; Scoppola et al. 2006). Plate motions follow a sinusoidal flow, oriented roughly westward in the Atlantic Ocean but turning west-northwestward in the Pacific Ocean and finally bending southwestward in Asia (Crespi et al. 2007). Referring to such mainstream of plate motion, we identify two end members of subduction zones, associated with two fundamental types of orogens.

Westward subduction zones oppose mantle flow and tend to be steeper. Décollement planes are shallow and affect only the upper layers of the downgoing plate. Low-relief, thin-skinned, singly vergent orogens are produced, chiefly consisting of volcanic or sedimentary rocks (e.g., Lesser Antilles, Sandwich, Apennines, Carpathians, Banda, Tonga, Marianas, Nankai, Kurili, Aleutians; Doglioni et al. 2006).

Instead, eastward subduction zones follow mantle flow and are less inclined. Decollement planes cut across the whole crust, allowing the exhumation of deep-seated rocks. High-relief, thick-skinned, doubly vergent orogens are produced (Koons 1990, Willett et al. 1993), largely consisting of neometamorphic and plutonic rocks (Andes, Alps, Caucasus, Zagros, Himalayas, Indonesia, Taiwan, New Zealand Alps; Doglioni et al. 2006).

As a general rule, the subduction hinge moves away from the upper plate in westward subduction zones and toward the upper plate in eastward subduction zones. This dichotomy corresponds with the distinction between “pull-arc” and “push-arc” orogens (Laubscher 1988). Note that the term “eastward” is used loosely here to designate subduction zones that follow mantle flow, even if these are actually oriented northeastward in Eurasia (e.g., Himalayas) because of the undulated mainstream of plate motion (Crespi et al. 2007). If the net west-erly drift of lithospheric plates is controlled by Earth’s rotation, an astronomical mechanism that cannot be inverted, this model should be valid also for the geologic past.

**Geometries of Plate Convergence**

If the present is the key to the past, perhaps global paleotectonic and paleogeographic reconstructions should be based on the actualistic hypotheses that … backarc spreading occurs where arc orogens face east, and that backarc thrusting occurs where arc orogens face west. (Dickinson 1988, p. 20)

Subduction involves a lower downgoing plate and an upper overriding plate, both of which can be either oceanic or continental. By considering all possible basic combinations between subduction polarity (westward vs. eastward) and nature of converging plates (oceanic vs. continental), the types of plate convergence are reduced to eight end members (fig. 1). The pro side of the orogen is the one facing the subduction zone.

**Westward Intraoceanic Subduction.** Westward intraoceanic subduction is widespread along the western Pacific (e.g., Philippines and Marianas) and occurs in the western Atlantic (Lesser Antilles and South Sandwich Islands) and western Mediterranean Sea (Aeolian Islands). The age of the oceanic crust is syn-subduction in the back-arc basin and generally much older in the lower plate. The arc-trench system formed above the subduction zone includes calc-alkaline igneous rocks (arc massif) and oceanic rocks scraped off the subducting plate (oceanic prism).

**Westward Subduction of Oceanic Lithosphere beneath Continental Lithosphere.** This setting is typical of newly formed westward subduction zones,
Figure 1. Eight true-scale schematic diagrams illustrate different styles of orogenic deformation for the eight identified scenarios of plate convergence. Orogens are made of rocks accreted from the lower and/or upper plates; shades of continental crust highlight upper plate (dark brown) versus lower plate (light brown) contributions. East-facing, singly vergent, and low-relief prisms largely consist of deformed lower-plate rocks \([A, D]\). West-facing, doubly vergent, and high-relief orogens mostly consist of deformed upper-plate rocks in precollisional stages \([F]\), lower-plate rocks being massively involved only during final continental collision \([G, H]\). High-pressure neometamorphic rocks, exhumed in west-facing orogens, are light blue. The profound global asymmetry between east-facing versus west-facing orogens and subduction zones can be fully appreciated only when the mainstream of plate motions is recognized.
which may develop along the retro side of thick-skinned orogens generated by preexisting eastward subduction (e.g., initiation of Barbados subduction; Doglioni et al. 1999). Large crustal slices of the in-active orogen are boudinaged during progressing back-arc extension and dragged eastward while the subduction hinge migrates away from the upper plate (e.g., Calabria and pre-Pleistocene of northern Japan; Doglioni et al. 1998).

The pro side of the orogen is an accretionary prism, developed at the expense of the uppermost layers of the subducting plate and largely represented by oceanic sediments (e.g., Nankai Trough; Moore et al. 1990). Perhaps the best modern example is northern New Zealand, where the oceanic Pacific Plate subducts beneath stretched continental lithosphere [Henrys et al. 2006]. The upper-plate crustal extension is propagating southward across the low-topography North Island, unzipping the nascent Taupo back-arc basin (Parson and Wright 1996; Beanland and Haines 1998). Subduction polarity changes farther south, where South Island is instead characterized by a doubly vergent, high-topography compressional orogen produced by continental collision (Beaumont et al. 1996b).

Westward Subduction of Continental Lithosphere beneath Oceanic Lithosphere. At the final stage of oceanic subduction or laterally to an active oceanic segment (e.g., Banda Arc), thinned continental lithosphere may be pulled down to 100–250 km (Müller and Panza 1986; Ranalli et al. 2000), until subduction is eventually throttled by buoyant lithosphere of closer-to-normal thickness (e.g., Southern Apennines).

East-facing singly vergent orogens formed above westward subduction zones are characterized by low structural relief (Doglioni et al. 1999). The pro side of the orogen is a thin-skinned thrust belt (including sedimentary sequences originally deposited on a continental paleomargin and frontally accreted turbidites), whereas its retro side is a magmatic arc (better developed if subduction is faster; Tatsumi and Eggins 1995).

Because little sediment is produced by the low-relief orogen and tectonic subsidence is one order of magnitude greater than for eastward subductions (Doglioni 1994), the sedimentary basin formed both in front of and above (Ori and Friend 1984) the growing accretionary prism typically remains persistently in deepwater conditions (“foredeep”). Foredeeps formed above westward-subducting continental margins are contrasted here with less sub-sident foreland basins associated with high-relief Alpine-type collision orogens, which are rapidly over-filled with shallow-marine to fluvial sediments (Doglioni 1994).

Westward Subduction of Continental Lithosphere beneath Continental Lithosphere. This case differs from the one described above only because extension on the retro side of the orogen is insufficient to tear the crust, and an ensialic back-arc basin develops (e.g., Pannonian Basin in the rear of the Carpathians; Horvath 1993). This has no systematic influence on the structure of the orogen and, thus, on tectonigenic supply.

Eastward Intraoceanic Subduction. The few modern examples include the Vanuatu (New Hebrides), where a doubly vergent intraoceanic prism has been produced by collision of the volcanic arc with oceanic plateaus, submarine ridges, and seamounts (Taylor et al. 1995; Meffre and Crawford 2001). Eastward subduction also takes place along highly oblique intraoceanic convergence zones beneath the Macquarie Ridge (Massell et al. 2000) and the Andaman Sea, a young pull-apart oceanic basin (Curray 2005). The Andaman-Nicobar Ridge is a tectonic stack of arc-derived and remnant-ocean turbidites capped by forearc ophiolites (Allen et al., forthcoming). Ophiolites represent the only sub-aerial exposure of the Macquarie Ridge (Rivizzigno and Karson 2004).

Eastward Subduction of Oceanic Lithosphere beneath Continental Lithosphere. The classic example is the eastern Pacific, bordered by a continuous high-relief cordillera from Alaska to the Andes (Jaillard et al. 2002). Because viscosity is much higher in the lower oceanic plate, shortening is mostly concentrated in the upper continental plate, and the orogen chiefly consists of upper-plate material (table 1). The lower plate may be subducted entirely, and even tectonic erosion commonly takes place because of this marked rigidity contrast (von Huene and Lallemand 1990; Ranero and von Huene 2000). In contrast, accretion typically occurs where the lower plate is overlain by thick deep-sea turbidites (e.g., Alaska and Sumatra; Dickinson 1995; Ingersoll et al. 2003).

The pro side of the orogen is an arc-trench system, with a forebelt of variable width cored by basement rocks (von Huene 1986). The retro side is a thick-skinned thrust belt also involving basement but frequently propagating toward the foreland in thin-skinned mode (e.g., Rocky Mountains; Bally et al. 1966).

The orogen generally undergoes compression and uplift, but extension may develop where motion of the lower plate has been inverted after subduction of a mid-ocean ridge (e.g., Basin and Range) or where
distinct subplates override the lower plate at different velocities (e.g., Aegean Sea; Doglioni 1995). When we consider the undulated mainstream of plate motions, the Sumatra-Java arc belongs to this category.

**Eastward Subduction of Continental Lithosphere beneath Oceanic Lithosphere.** This setting represents the final stage of eastward intraoceanic subduction, when a continental margin arrives at an intraoceanic trench. Virtually intact slabs of dense oceanic upper-plate lithosphere can thus be emplaced onto buoyant continental crust (“obduction”; Coleman 1971; Karig 1982). Such a process gives rise to “ophiolite-capped thrust belts” (Cawood 1991), the archetypal example being the Northern Oman orogen assemled at Late Cretaceous times (Searle and Stevens 1984). The pro side of the obduction orogen is a thick-skinned thrust belt, beneath which continental blueschists and eclogites of the axial belt may be exposed. Its tectonic lid consists of a complete section of forearc mantle and crust, generated synchronously with subduction and detached along a mechanically weak boundary as deep as the asthenosphere (Spray 1984; Searle and Cox 1999).

**Eastward Subduction of Continental Lithosphere beneath Continental Lithosphere.** This setting represents the final stage of eastward oceanic subduction, when two continental margins collide. Doubly vergent Alpine-type orogenic prisms with high structural and topographic relief are thus produced (Doglioni et al. 1999). The axial part of the orogen includes slivers of strongly thinned outer continental margins and adjacent oceanic lithosphere that underwent high-pressure metamorphism in the early subduction stage of collision (Beaumont et al. 1996a). Because thrust planes cut across the lithosphere, deeply subducted eclogitic rocks can be exhumed in a few million years (Rubatto and Hermann 2001; Baldwin et al. 2004). Thick-skinned thrust belts formed along both external sides of the orogen include inner parts of collided paleomargins underlain by continental crust of closer-to-normal thickness as well as frontally accreted foreland-basin clastics. In external belts, close to the contact with the axial belt, orogenic metamorphism may reach amphibolite facies (Frey and Ferreiro Mählmann 1999).

Collision orogens are by no means all alike, and major differences are displayed by two of the best-known examples belonging to the same orogenic system, the Alps and the Himalayas. The Himalayas have a much better developed arc-trench system, which can be traced for ∼3000 km from Pakistan to Myanmar (Gansser 1980). The axial belt of the Alps includes a stack of both continental and oceanic nappes showing widespread high-pressure metamorphism. In contrast, in the Himalayas, the axial belt is confined to a narrow wedge largely consisting of amphibolite-facies metasediments extruded between a main thrust zone at the base and a major detachment system at the top (Hodges 2000); oceanic units are lacking, and eclogites have been recognized only locally so far (Lombardo and Rolfo 2002). The retro side of the Alps consists of

<table>
<thead>
<tr>
<th>Lithosphere</th>
<th>Examples</th>
<th>Source of accreted rock units</th>
<th>Process of prism building</th>
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<tbody>
<tr>
<td>Westward subduction:</td>
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<tr>
<td>O/O</td>
<td>Marianas, Sandwich</td>
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<tr>
<td>C/O</td>
<td>N. New Zealand, Calabria</td>
<td>Inherited upper plate + lower plate</td>
<td>Oceanic offscraping</td>
<td>Boudinaged belt and prism</td>
</tr>
<tr>
<td>O/C</td>
<td>Banda, S. Apennines</td>
<td>Inherited upper plate + lower plate</td>
<td>Continental offscraping</td>
<td>Boudinaged belt and prism</td>
</tr>
<tr>
<td>C/C</td>
<td>Carpathians, N. Apennines</td>
<td>Inherited upper plate + lower plate</td>
<td>Continental offscraping</td>
<td>Boudinaged belt and prism</td>
</tr>
<tr>
<td>Eastward subduction:</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>O/O</td>
<td>Andamans, Vanuatu</td>
<td>Upper plate + lower plate</td>
<td>Oceanic collision</td>
<td>Intraoceanic prism</td>
</tr>
<tr>
<td>O/C</td>
<td>Andes, Cascades</td>
<td>Mostly upper plate</td>
<td>Continental buckling</td>
<td>Cordillera</td>
</tr>
<tr>
<td>C/O</td>
<td>Oman, Papua</td>
<td>Upper plate + lower plate</td>
<td>Obduction</td>
<td>Obduction orogen</td>
</tr>
<tr>
<td>C/C</td>
<td>Himalayas, Alps</td>
<td>Upper plate + lower plate</td>
<td>Continental collision</td>
<td>Collision orogen</td>
</tr>
</tbody>
</table>

Note. Westward subduction = low relief, thin-skinned, singly vergent, “pull-arc” orogens with rapid subsidence of trench or foredeep, oceanic (or ensialic) back-arc basin. Eastward subduction = high relief, thick-skinned, doubly vergent “push-arc” orogens with slower subsidence of trench or foreland basin, no true back-arc basin. O = oceanic, C = continental. Topographic relief, deformation style, and rock units involved are largely controlled by subduction polarity. The illustrated end-member orogens may evolve dynamically through geologic time. When a continental margin arrives at the oceanic trench, pull-arc orogens (Laubscher 1988) evolve from northern New Zealand type to Banda type (or Carpathian type), ophiolite-capped push-arc orogens from Andaman type to Oman type, and higher-topography push-arc orogens involving continental rocks in the hanging wall of the subduction zone from Andean type to Himalayan type.
a well-defined, 50–100-km-wide, thick-skinned thrust belt, whereas the deformed retro side of the Himalayas is much broader and includes the vast Tibetan plateau as well as a series of highly elevated mountain chains (e.g., Hindukush-Karakorum, Pamir, and Tian Shan). Both external belts of the Alps include deep-sea turbidites ranging in age from Cretaceous to Miocene, whereas foreland-basin clastics accreted along the front of the Himalayas chiefly include Neogene fluvial sediments (Burbank et al. 1996; Najman 2006).

Classification of Orogenic Sediment Provenances

Given the potential diversity of recycled orogenic sediment, it is a severe challenge to devise a scheme for its identification and classification that has empyric validity for interpretation of the sedimentary record. (Dickinson 1985, p. 347)

Because orogenic belts are composite structures including diverse rock complexes assembled in various ways by geodynamic processes, orogenic detritus embraces a varied range of signatures. Unraveling provenance of clastic wedges accumulated in foreland basins, foredeeps, or remnant-ocean basins is, therefore, an arduous task that requires a sophisticated conceptual reference scheme.

The Dickinson Model. Orogenic detritus derives either from volcano-plutonic rock suites generated along active intraoceanic and continental arcs (magmatic-arc provenance) or from mainly sedimentary or metamorphic rocks tectonically uplifted within subduction complexes (subduction complex provenance), foreland fold-thrust belts (foreland uplift provenance), and collision orogens (collision orogen provenance; Dickinson and Suczek 1979). Subduction complex provenance is typified by chert-rich detritus from offscraped oceanic slivers and abyssal-plain sediments, whereas foreland uplift provenance is characterized by varied sedimentary lithics, moderately high quartz, and minor feldspars and volcanic lithic grains. Sediments from collision orogens also have typically intermediate quartz contents, high quartz/feldspar ratio, and abundant sedimentary and metasedimentary lithic fragments (Dickinson and Suczek 1979; Dickinson 1985).

Dickinson and Suczek (1979) and Dickinson (1985, 1988) recognized the intrinsically composite nature of detritus shed from orogenic belts into associated sedimentary basins but did not attempt to establish clear conceptual and operational distinctions among the three identified types of recycled orogenic provenances. For instance, subduction complex and collision orogen provenances may both include detritus from ophiolitic mélanges, and collision orogen and foreland uplift provenances may include detritus from magmatic arc remnants in relationship with relief distribution and drainage patterns (Dickinson and Suczek 1979, p. 2176–2178; Dickinson 1985, p. 350).

Observations from modern settings, where all factors affecting sediment composition can be verified, reveal discrepancies with the Dickinson model. Ophiolitic detritus is only marginally dealt with. Large, subaerially exposed subduction complexes chiefly consist of offscraped turbidites and thus typically shed abundant shale/slate grains rather than chert (Garzanti et al. 2002a; E. Garzanti, data from the Indo-Burman Ranges). Detritus from remnants of continental paleomargins incorporated within thrust belts shows close affinities with anorogenic detritus of continental block provenance (Garzanti et al. 2003, 2006). Collision orogens produce a wide range of lithic/quartzolitic to quartzofeldspathic signatures, including all possible mixtures of both first-cycle and multicycle detritus from neometamorphic, paleometamorphic, plutonic, volcanic, and sedimentary rocks. Further problems are caused by recycling of clastic wedges.
accreted at the orogenic front (Garzanti et al. 2002a, 2004b, 2005).

As pointed out by Ingersoll (1990, p. 733), most of these complexities cannot be successfully handled because “third-order fields (magmatic arc, recycled orogen, and continental block) are useful for continental-scale analyses,” whereas “second-order fields (e.g., undissected, transitional, and dissected arcs of Dickinson 1985) are useful at the scale of mountain ranges and basins.” In order to improve on the resolution of provenance models, this article focuses on the structure of single orogenic belts rather than on whole continents and ocean basins.

A Refined Two-Step Model for Orogenic Sediment Provenance. The scheme presented here is based on the simple observation that the complicated tectonic structure of composite orogens results from the juxtaposition and superposition of a limited number of geological domains, each including genetically associated rock complexes elongated subparallel to the orogen’s strike. Because major rivers reach well into the core of the composite orogen, sediments supplied to the associated basins are invariably a mixture of detritus from different types of such linear domains (Dickinson and Suczek 1979). If mixed detrital signatures are too varied to be modeled directly, then their complexity can be handled by operating in two steps. We focus first on detrital modes produced by each distinct type of orogenic domain (primary orogenic provenances) and only subsequently recombine the appropriate types of primary provenances to model detrital suites recorded in sedimentary basins (composite orogenic provenances).

Five types of orogenic domains are identified here as the primary building blocks of composite orogenic prisms: [1] magmatic arcs (autochthonous or allochthonous sections of arc crust), [2] accreted or obducted ophiolites (largely intact allochthonous sections of oceanic lithosphere), [3] neometamorphic axial belts (polydeformed slivers of distal continental margin crust and adjacent oceanic lithosphere that have undergone high-pressure to high-temperature metamorphism during subduction and subsequent exhumation), [4] paleomargin remnants (only weakly metamorphosed allochthonous sections of continental basement and/or overlying platform to pelagic strata), and [5] orogenic clastic wedges (accreted foreland-basin, foredeep, or remnant-ocean-basin terrigenous sequences).

As shown by provenance studies in modern orogenic settings from the Mediterranean Sea to the Indian Ocean, detritus produced by the erosion of each single orogenic domain is characterized by unique detrital modes, heavy-mineral assemblages and unroofing trends, which can be predicted and modeled. The five types of orogenic domains thus correspond to five types of primary sediment provenance (fig. 2).

Our scheme expands on the original Dickinson model, with the following main modifications: [1] magmatic arc provenance is unchanged, [2] ophiolite provenance is recognized as a new provenance type, [3] axial belt provenance is defined as the most distinctive type of collision orogen provenance, [4] marked affinities between foreland uplift provenance (a type of orogenic sediment provenance in Dickinson and Suczek 1979) and continental block provenance (the anorogenic sediment provenance in Dickinson and Suczek 1979) are emphasized, [5] clastic wedge provenance is newly defined, in order to single out, and put emphasis on, the thorny problem of sediment recycling. This latter provenance type consists entirely of recycled orogen-derived detritus, whereas the former four types chiefly consist of first-cycle detritus [with the limited exceptions of grains recycled from forearc basin strata exposed in arc domains or from sandstone-bearing passive-margin strata intercalated within paleomargin successions].

Such a moderate increase in complexity is held as necessary and sufficient to appropriately handle the full variety of cases observed along modern subduction zones. The proposed scheme is flexible enough to reproduce the complete range of mixed detrital signatures issued during erosional denudation of composite orogens and to predict the evolution of detrital modes and heavy-mineral assemblages as recorded in space and time by clastic wedges deposited in arc-related, foreland, foredeep, and remnant-ocean basins (table 2).

Primary Provenances and Unroofing Trends

Data for modern marine and terrestrial sands from known tectonic settings provide standards to evaluate the effect of tectonic setting on sandstone composition. (Dickinson and Suczek 1979, p. 2164)

The information contained in this section is based on provenance studies of modern sediments produced and deposited in areas characterized mostly by arid climate and/or high relief. The described compositional signatures can thus be considered as unaffected by significant chemical weathering and diagenetic dissolution and to faithfully reflect plate-tectonic setting and lithology of source terranes. Such primary detrital modes can be used as a reference for assessing provenance of ancient clas-
<table>
<thead>
<tr>
<th>Primary orogenic provenances</th>
<th>Indo-Burman-type subduction complexes</th>
<th>Apennine-type thin-skinned orogens</th>
<th>Oman-type obduction orogens</th>
<th>Andean-type cordilleras</th>
<th>Alpine-type collision orogens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magmatic arc</td>
<td>Minor (largely recycled)</td>
<td>Dominant locally (retro side)</td>
<td>Minor locally (retro side)</td>
<td>Dominant (pro side)</td>
<td>Significant locally (early stage → undissected arc; late stage → dissected arc)</td>
</tr>
<tr>
<td>Ophiolite</td>
<td>Significant locally (retro side)</td>
<td>Dominant locally (subduction complex remnants)</td>
<td>Dominant (early stage)</td>
<td>Significant locally (pro side)</td>
<td>Significant locally (early stage)</td>
</tr>
<tr>
<td>Axial belt</td>
<td>Insignificant</td>
<td>Dominant locally (boudinated remnants)</td>
<td>Significant locally (late stage)</td>
<td>Significant locally (pro side)</td>
<td>Dominant (late stage)</td>
</tr>
<tr>
<td>Continental block</td>
<td>Significant locally (incorporated terranes)</td>
<td>Major</td>
<td>Dominant locally (late stage)</td>
<td>Dominant (retro side)</td>
<td>Major (late stage)</td>
</tr>
</tbody>
</table>

Note. The diagnostic detrital modes produced by each distinct orogenic domain are first identified [primary orogenic provenances] and next appropriately recombined to describe detrital suites recorded by arc-related, foreland, foredeep, and remnant-ocean basin fills [composite orogenic provenances]. Locally significant to locally dominant provenances may characterize first- to second-order-scale samples, whereas detritus of mixed provenance is invariably recorded at third-order scale [e.g., big rivers, Ingersoll 1990].
tic suites deposited in comparable geodynamic settings or for inferring compositional modifications caused by intense weathering in hot humid climates or diagenesis.

High-resolution bulk petrography data were collected by the Gazzi-Dickinson method (Ingersoll et al. 1984; Garzanti and Vezzoli 2003) on river and beach sands derived from single homogeneous orogenic domains (first- to second-order sampling scales of Ingersoll 1990). Further quantitative information on heavy-mineral assemblages is provided in Garzanti and Andò (2007b).

**Magmatic Arc Provenances.** Volcanic detritus from basaltic, andesitic, and rhyodacitic lavas and ignimbrites representing the arc cover consists of volcanic lithic grains, plagioclase, and pyroxenes (fig. 3G, Undissected Magmatic Arc Provenance; Marsaglia and Ingersoll 1992). Plutonic detritus from diorite-granodiorite batholiths representing the plutonic roots of the arc massif chiefly includes quartz, plagioclase, K-feldspar, and mainly blue-green hornblende (figs. 3F, 4D, Dissected Magmatic Arc Provenance). The ideal compositional trend recorded by terrigenous sequences accumulated in forearc and other arc-related basins during unroofing of the arc massif is, therefore, characterized by the progressive increase of quartz, K-feldspar, and blue-green hornblende at the expense of volcanic lithic grains and pyroxenes (Dickinson 1985; Garzanti and Andò 2007b).

**Ophiolite Provenance.** Tectonically accreted or obducted sections of oceanic lithosphere, which escaped subduction and orogenic metamorphism, shed mafic to ultramafic detritus with peculiar petrographic and mineralogical features (Nichols et al. 1991). Distinct signatures characterize sediments supplied during unroofing of progressively deeper stratigraphic levels of the multilayered oceanic lithosphere. Pillow lavas and sheeted dikes of the upper crust shed lithwork volcanic to altered diabase lithic grains and clinopyroxene or low-grade minerals grown during oceanic metamorphism (e.g., actinolite and epidote). Orthopyroxene-phryic boninite grains may be common in detritus from suprasubduction-zone ophiolites (fig. 5D; Bloomer et al. 1995; Garzanti et al. 2000). Plutonic rocks of the lower crust supply cumulate, gabbro, and plagiogranite rock fragments, calcic plagioclase, diopсидic clinopyroxene, and green/brown hornblende; hypersthene grains may reflect the hydrous, arc-related character of late-stage magmatic source rocks. Serpentinized mantle harzburgites supply lizardite-serpentinite grains with pseudomorphic cellular texture, enstatitic orthopyroxene, olivine, and rare chrome spinel (figs. 3E, 5E; Garzanti et al. 2002b).

**Axial Belt Provenance.** Detritus supplied by the axial pile of neometamorphic nappes representing the central backbone of collision orogens is influenced by several factors, including metamorphic grade of source rocks and relative abundance of continental versus oceanic protoliths. Metasedimentary cover nappes shed lithic to quartzolithic detritus, including metapelite, metapsammite, and metacarbonate grains of various ranks (figs. 3A, 4B, 5A); only amphibolite-facies metasediments supply abundant heavy minerals (e.g., almandine garnet, stauroliite, kyanite, sillimanite, and diopsidic clinopyroxene). Continental basement nappes shed hornblende-rich quartzofeldspathic detritus (figs. 3B, 4A). Largely retrogressed blueschist to eclogite-facies metaophiolites supply albite, metabasite, and foliated antigorite-serpentinite (serpentinite schist) grains (fig. 4C), along with abundant heavy minerals (e.g., epidote, zoisite, clinozoisite, actinolitic to barroisitic amphiboles, glauconephite, omphacitic clinopyroxene, and lawsonite).

Increasing metamorphic grade and/or deeper tectonostratigraphic level of source rocks may be reflected by (a) increasing rank of metamorphic rock fragments (as indicated by progressive development of schistosity and growth of micas and other index minerals; metamorphic index of Garzanti and Vezzoli 2003), (b) increasing feldspars, (c) increasing heavy-mineral concentration (heavy-mineral concentration index of Garzanti and Andò 2007a), (d)...

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**Figure 3.** Detrital modes of modern sands from the Apenninic thin-skinned orogen. Shown are river and beach samples derived from one single geological domain or subdomain (Garzanti et al. 2002a; first-order sampling scale of Ingersoll 1990). Also shown are fields for the 10 largest rivers on each side of the orogen (E. Garzanti, unpublished data; second-order sampling scale of Ingersoll 1990). All of these carry recycled detritus of elastic wedge provenance, associated with lithic sedimentary detritus of undissected continental block provenance (Adriatic rivers draining the pro side of the orogen) or with feldspatholithic to arkosic detritus of magmatic arc provenance (Thyrrenian rivers draining the retro side of the orogen). Detritus from remnants of the Alpine subduction complex and axial belt are locally dominant (Northern Apennines and Calabria, respectively). Petrographic parameters, symbols, provenance fields, and confidence regions about the mean as in figure 2. Scale bar = 250 μ; all photos with crossed polars.
increasing hornblende, changing progressively in color from blue/green to green/brown (hornblende color index of Garzanti et al. 2004b), and [ε] successive appearance of chloritoid, staurolite, kyanite, fibrolitic, and prismatic sillimanite (metasedimentary minerals index of Garzanti and Ando 2007b).

**Continental Block Provenience.** Allochthonous platform to pelagic strata, representing the tectonically dismembered remnants of sedimentary successions originally deposited on a continental paleomargin, supply diverse sedimentary to low-rank metasedimentary grains (e.g., limestone, dolostone, chert, shale, slate, and metacarbonate; figs. 3H, 4F; fig. 5B, 5C, Undissected Continental Block Provenience), locally associated with quartz, feldspars, or volcanic/metavolcanic rock fragments recycled from interbedded siliciclastic or volcanioclastic units. Tectonically imbricated basement units shed quartzolithic to quartzofeldspathic sands with micas, garnet, staurolite, kyanite, sillimanite, hornblende, epidote, or pyroxenes (fig. 4E, Dissected Continental Block Provenience).

Detritus supplied by paleomargin remnants incorporated within thick-skinned thrust belts varies markedly during unroofing of deep-seated basement rocks. Heavy-mineral concentration progressively increases, and detrital modes ideally change from lithic sedimentalclastic or locally sedimentalclastic-volcanioclastic (cover sequences) to quartzolithic, quartzofeldspathic, and feldspathic metamorphiclastic signatures (greenschist-facies to granulite-facies basement units; Garzanti et al. 2006). Instead, thin-skinned orogens associated with westward subduction zones mostly incorporate cover strata, which invariably supply lithic sedimentary detritus with various amounts of recycled quartz.

**Clastic Wedge Provenience.** Sand recycled from fluvial to turbiditic foreland-basin, foredeep, or remnant-ocean-basin clastic sequences tend to reproduce the composition of orogen-derived (and thus typically quartzolithic; Dickinson 1985) parent sandstones, generally with significant addition of labile mudrock grains (fig. 3C, 3D; fig. 4G; Cavazza et al. 1993; Fontana et al. 2003). Because unstable minerals are extensively dissolved during diagenesis of parent sandstones, recycled heavy-mineral assemblages include only stable to ultra-stable species and have very low concentrations (Garzanti et al. 2002a; Garzanti and Ando 2007a).

**Composite Orogenic Provenances**

Complex orogenic belts may include all three kinds of provenance in subparallel linear belts which may jointly contribute mixed detritus to varied successor basins. Arc-derived detritus may also be incorporated into such mixed suites. (Dickinson and Suczek 1979, p. 2176)

In order to illustrate how primary provenances may combine in different scenarios of plate convergence and give rise to composite orogenic provenances, we follow an exemplary rather than exhaustive approach. We describe the signatures of sediments supplied by a large subduction complex (Indo-Burman Ranges and Andaman Islands), by a thin-skinned orogen produced by westward subduction (Apennines), and by three types of thick-skinned composite orogens produced by eastward subduction of continental-beneath-oceanic (Oman obduction orogen), oceanic-beneath-continental (Andean cordillera), and continental-beneath-continental lithosphere (Alpine and Himalayan collision orogens).

**Detritus from the Indo-Burman-Andaman Subduction Complex.** Subduction complexes large enough to be exposed subaerially and become significant sources of terrigenous detritus are typically formed by tectonic accretion above trenches choked with thick sections of remnant-ocean turbidites (Ingersoll et al. 2003). This is the case of the outer ridge extending from the Indo-Burman Ranges to offshore Sumatra, which largely consists of accreted abyssal-plain sediments ultimately derived from the rising Himalayas and locally overthrust by volcanioclastic and ophiolitic forearc sequences (Curray 2005; Allen et al., forthcoming). Modern sands from the Indo-Burman Ranges and Andaman Islands con-

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**Figure 4.** Detrital modes of modern sands derived from the Alpine collision orogen. Shown are river samples derived from one single geological domain or subdomain (Garzanti et al. 2004b, 2006). Major rivers (Rhône, Rhein, Inn, Salzach, Mur, Drau, Adige, and Po) carry mixed detritus mostly supplied by axial belt neometamorphic rocks and by continental block paleometamorphic and sedimentary rocks in various proportions. Petrographic parameters, symbols, provenance fields, and confidence regions about the mean as in figure 2. Profile modified after Polino et al. (2002). Scale bar = 250 µm; all photos with crossed polars.
sist of quartz and feldspars recycled from turbiditic sandstones, with various amounts of shale/slate grains shed from turbiditic mudrocks (clastic wedge provenance). Ultramafic and mafic detritus is supplied locally from accreted forearc ophiolites (ophiolite provenance). Additional volcanic detritus and chert grains are recycled from arc-derived and deep-water sediments of the forearc basin (fig. 6).

**Detritus from the Apenninic Thin-skinned Orogen.** Modern sands from the Apennines are derived from diverse source rocks, including pelagic cherty limestones and carbonate platforms of the Apulian paleomargin (undissected continental block provenance), foredeep turbidites accreted along the pro side of the orogen (clastic wedge provenance), and volcanic or locally plutonic rocks exposed along its retro side (magmatic arc provenance). Because westward Apenninic subduction started in the late Paleogene along the retro side of eastward Alpine subduction (Doglioni et al. 1998), the composite Apenninic orogen is capped by the proto-Alpine subduction complex, including remnant-ocean turbidites and accreted ophiolites, and incorporates boudinaged greenschist-facies to amphibolite-facies remnants of the Alpine axial belt (fig. 3). Because of modest tectonic uplift, erosional unroofing is limited and the spatial distribution of detrital signatures is largely controlled by geological inheritance (Garzanti et al. 2002a).

**Detritus from the Oman Obduction Orogen.** Modern sands from the Oman obduction orogen are mainly derived from mafic and ultramafic rocks occupying the highest structural position of the tectonic pile. Sedimentary rock fragments, subordinate quartz, and metamorphic detritus are supplied by frontally accreted to deeply subducted continental margin rocks exposed in tectonic windows (fig. 5; Garzanti et al. 2002b). Where and when erosion bites into deeper structural levels, detritus of ophiolite provenance is thus mixed with, and finally ideally replaced by, detritus of continental block and axial belt provenances.

**Detritus from the Andean Cordillera.** Modern sands from the Andes show a marked asymmetry. Volcano-plutonic detritus is dominant along the pro side of the cordillera, whereas quartzolithic to quartzose detritus with abundant metamorphic lithic grains characterize its retro side (fig. 7; Potter 1994). Sediments in the Peru-Chile Trench range from undissected-arc provenance adjacent to areas of active volcanism, to transitional-arc and dissected-arc provenances where the batholithic roots of the inactive arc massif have been uplifted and widely exposed along the Cordillera Occidental (Yerino and Maynard 1984; Thornburg and Kulm 1987). Sediments shed by metamorphic to granitoid basement rocks and Paleozoic to Mesozoic strata of the Cordillera Oriental and Subandean thrust belt display continental block provenance and are invariably mixed with subordinate volano-plutonic detritus from the arc massif (DeCelles and Hertel 1989). Recycling of weathered orogenic detritus (clastic wedge provenance) leads to a marked increase in quartz across subequatorial lowlands (Johnsson et al. 1988).

**Detritus from the Alpine and Himalayan Collision Orogens.** Modern sands from the Alps and the Himalayas chiefly include quartz, feldspars, metamorphic rock fragments, micas, and amphibole-garnet-epidote heavy-mineral assemblages, reflecting major supply from partially retrogressed high-pressure (e.g., Penninic Domain) to high-temperature (e.g., Greater Himalaya) neometamorphic rocks of the high-topography and rapidly exhumed axial belt. Similar signatures, however, may characterize first-cycle detritus from paleometamorphic basements representing remnants of the continental margins caught in collision, as well as polycyclic detritus recycled from orogen-derived clastic wedges accreted along the mountain front (fig. 4; Garzanti et al. 2004b, 2006).

In foreland-basin to remnant-ocean-basin successions, neometamorphic detritus of axial belt provenance can be differentiated from paleometamorphic detritus of continental block provenance only by using appropriate detrital geochronology techniques (Najman 2006). As a further complexity, allochthonous remnants of continental paleomargins not only are commonly overthrust by the axial belt and confined to external parts of the orogen (Helvetic Domain, Lesser Himalaya) but may also lie structurally above it, as a “tectonic lid” (Austroalpine Domain, Tethys Himalaya). External belts may directly face foreland basins on both sides of the orogen, where the axial belt is narrow and topographically subdued (e.g., Maritime and Eastern Alps).

The composition of foreland-basin sediments may change from volcaniclastic, ophioliticlastic, or sedimentalastic/low-rank metasedimentlastic in early syn-collisional stages, when detritus from volcanic arcs and subduction complexes may be dominant (“Taiwan stage”; Dorsey 1988; Garzanti et al. 1996; Najman and Garzanti 2000), to high-rank neometamorphiclastic at later collisional stages, when the axial metamorphic core of the orogen starts to be rapidly exhumed (White et al. 2002). Focused erosion of rapidly uplifted gneiss domes may then produce huge volumes of hornblende-rich quartzofeldspathic detritus that typically exceed
Figure 5. Detrital modes of modern sands from peri-Arabian obduction orogens. Shown are river and beach samples derived from one single geological domain or subdomain (Garzanti et al. 2000, 2002). Crust-derived feldspatholithic detritus to mantle-derived lithic detritus of ophiolite provenance is shed by the oceanic upper plate, whereas sedimentary to neometamorphic metasedimentary and metavolcanic detritus of continental block to axial belt provenances is shed by the continental lower plate. Petrographic parameters, symbols, and confidence regions about the mean as in figure 2. Scale bar = 250 μ, all photos with crossed polars.

The storage capacity of associated foreland basins and can even reach totally unrelated sedimentary basins thousands of kilometers away (Ingersoll et al. 2003; Garzanti et al. 2004a, 2004b). Volcanic or ophiolitic detritus becomes volumetrically insignificant, but contributions from dissected-arc massifs may remain locally prominent (Garzanti et al. 2005). Because of the progressive lateral growth of external belts, which shield the foreland basin from axial belt detritus, compositional trends may revert...
in time to sedimentaclastic/low-rank metasedimentaclastic (White et al. 2002). Detrital signatures of foreland-basin sediments are controlled by the entry points of high-rank neometamorphiclastic detritus carried by major rivers draining the axial belt and thus vary irregularly along strike and are strongly dependent on drainage changes (Muttoni et al. 2003; Najman et al. 2003).

**Conclusions**

Provenance interpretations for sedimentary assemblages can be addressed most effectively in the context of global paleogeographic patterns inferred from paleotectonic reconstructions and can be used to test such reconstructions (Dickinson 1988, p. 22).

Orogenes formed at convergent plate margins, representing topographically elevated sources of detritus, are composite geological structures of great complexity, including diverse rock units assembled in various ways by geodynamic processes. Orogenic sediments thus embrace a large range of mixed signatures, including variable proportions of both first-cycle and multicycle detritus from neometamorphic, paleometamorphic, sedimentary, and igneous rocks. Unraveling the provenance of orogen-derived terrigenous successions is consequently an arduous task that requires a detailed but, at the same time, simple and flexible reference model.

In order to establish a classification of orogenic belts and orogenic sediment provenances, we reduce the numerous possible plate interactions observed along subduction zones by selecting a limited number of variables (westward vs. eastward subduction polarity; oceanic vs. continental downgoing and overriding plates). Eight possible scenarios of plate convergence are thus recognized, each characterized by the tectonic assembly of a distinct type of composite orogen (fig. 1). As a further and most important simplification, we represent the structure of orogenic belts as a hierarchy of genetically associated rock complexes generated by tectonic and magmatic processes along subduction zones. The diversity of composite orogens is thus seen as resulting from juxtaposition and superposition of a limited number of subparallel geological domains.

Five types of such elongated orogenic domains
Detrital modes of modern sands from the Andean cordillera. Feldspatholithic suites of magmatic arc provenance characterize the west-facing pro side of the orogen [modes of deep-sea samples after Yerino and Maynard 1984 and Thornburg and Kulm 1987]. Instead, quartzolithic sands of continental block to clastic wedge provenance, showing increasing degree of chemical weathering toward lower equatorial latitudes [Johnsson et al. 1988], characterize the orogen’s east-facing retro side [modes of river samples after DeCelles and Hertel 1989]. Petrographic parameters, symbols, provenance fields, and confidence regions about the mean as in figure 2.

are identified as the primary building blocks of composite orogenic prisms: (1) magmatic arcs [autochthonous or allochthonous arc crust], (2) obducted or accreted ophiolites [allochthonous oceanic lithosphere], (3) neometamorphic axial belts [subducted continental margin crust or adjacent oceanic lithosphere], (4) paleomargin remnants [allochthonous continental crust], and (5) orogenic clastic wedges [allochthonous foreland-basin, foredeep, or remnant-ocean-basin fills].

Detritus produced by erosion of each of these primary orogenic domains is characterized by specific detrital modes, heavy-mineral assemblages, and unroofing trends, which can be predicted and modeled. The five primary orogenic domains thus correspond to five [four chiefly first-cycle and one polycyclic] primary types of sediment provenances; this refines and expands on the classic model proposed by the Dickinson school in the late 1970s [fig. 2]. As a final step, the complexity of detrital signatures produced by each type of composite orogen as a whole may be represented as resulting from a limited number of combinations of the five primary provenances in various proportions [figs. 3–7].

This relatively simple scheme is flexible enough to describe the complete range of mixed detrital signatures observed along modern subduction zones from the Mediterranean Sea to the Indian and Pacific oceans. It is thus proposed here as a conceptual tool to model the composition of sediments produced by erosional denudation of composite orogenic systems and to predict the evolution of detrital modes and heavy-mineral assemblages as recorded in space and time by clastic successions deposited in arc-related, foreland, foredeep, and remnant-ocean sedimentary basins.

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