Chapter 29

PLATE TECTONICS AND HEAVY MINERAL SUITES OF MODERN SANDS

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ABSTRACT

This contribution classifies detrital heavy mineral assemblages produced in contrasting geodynamic settings, following the provenance scheme proposed by Dickinson and co-workers in the late 1970s. The vital link with bulk-sediment detrital modes was established by systematically coupling high-resolution heavy mineral and petrographic analyses on the same sample sets, in a series of actualistic provenance studies carried out in key geological areas, characterised by arid to semiarid climate.

Quartzofeldspathic to quartzose sands of "Continental Block Provenance" contain either heavy-mineral-rich, hornblende-dominated assemblages derived from amphibolite-facies basements exposed along rift escarpments and in cratonic shields, or heavy-mineral-poor suites with commonly rounded ultrastable grains recycled from cover strata. Volcanic rifted margins shed lithofeldspathic detritus with clinopyroxene-dominated suites (largely lilac-brown Ti-rich augite) that commonly include olivine. Abundant clinopyroxenes (mostly green augite) and hypersthene, associated with olivine or dark-brown to reddish-brown hornblende (oxyhornblende), characterise feldspatholithic sands of "Magmatic Arc Provenance". The proportion of mainly blue-green hornblende increases progressively with erosion cutting deeper into the batholithic core of the arc massif. Quartzolithic sands of "Orogenic Provenance" include suites dominated by amphiboles, garnet, and epidote. The relative abundance of garnet (associated with subordinate staurolite, kyanite, and sillimanite) and blue-green to green-brown hornblende increases with increasing metamorphic grade of the sedimentary or igneous protoliths, respectively. Oman-type obduction orogens shed abundant heavy minerals, dominated by mafic and ultramafic minerals derived from the obducted ophiolite nappe. Apennine-type thin-skinned thrust belts provide heavy-mineral-poor assemblages recycled from accreted passive-margin successions or foredeep turbidites. Pyroxenes, derived from offscraped ophiolitic sequences, are locally present. The wealth of information heavy minerals provide on the geology of source areas makes their analysis an

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extremely powerful complementary tool in provenance studies of sediments not modified by diagenesis.

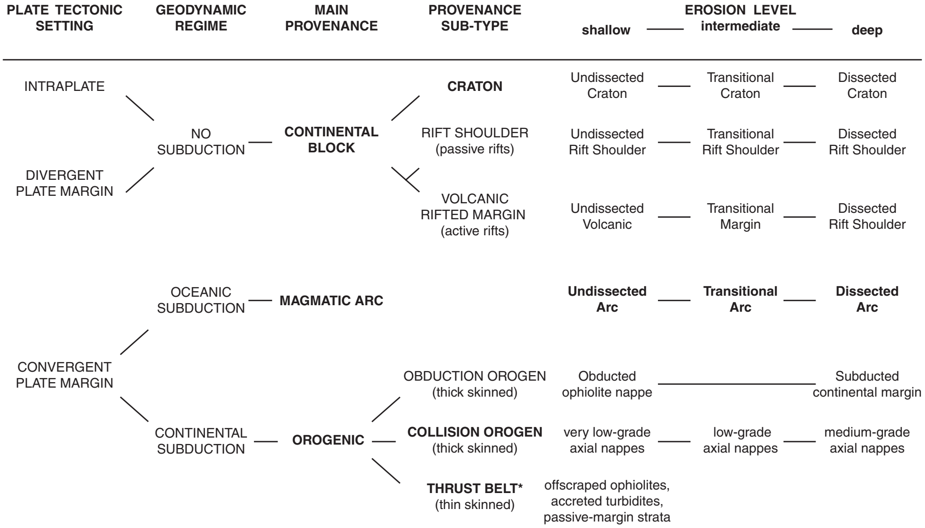
Keywords: heavy minerals; plate tectonics; continental rifts; cratons; magmatic arcs; orogenic belts

1. INTRODUCTION

The plate-tectonic revolution of the 1960s provided a new conceptual framework in which to interpret the evolution of the Earth's surface, leading to a new classification of sedimentary basins (Dickinson, 1974; Ingersoll and Busby, 1994). Petrologic models relating detrital modes of sands and sandstones to their geodynamic setting could thus be established (Dickinson and Suczek, 1979). Based on tabulated detrital modes of 88 worldwide terrigenous suites of Precambrian to Holocene age, Dickinson and Suczek defined three end-members: "Continental Block Provenance", "Magmatic Arc Provenance", and "Recycled Orogen Provenance", further subdivided into sub-provenances and evolutionary trends (Dickinson, 1985). Such an approach combined insight and simplicity, and represented a major breakthrough in clastic petrology. Subsequent years proved the Dickinson model to be successful in discriminating detrital signatures of contrasting plate-tectonic settings at continental scale (Ingersoll, 1990; Potter, 1994), provided that complexities of natural processes are taken into due account (including transition between tectonic regimes, long-distance transport, and modifications induced by chemical weathering or diagenesis: Mack, 1984; McBride, 1985; Johnsson, 1993).

A similar approach has been attempted for the chemical composition of sandstones (Schwab, 1975; Bathia, 1985), but with more limited success. Bulk-chemistry data in fact show large overlaps (Potter, 1978; Maynard et al., 1982) and are markedly influenced by a variety of processes (including grain size, mixing with intrabasinal grains, and diagenetic cementation, dissolution and replacement; Korsch et al., 1993), which are best recognised and assessed with the aid of the petrographic microscope (Roser and Korsch, 1986; Zuffa, 1987). The attempts made to investigate the relationships between heavy mineral suites and tectonic setting (Stattegger, 1987; Nechaev and Isphording, 1993) meet similar difficulties because of the great sensitiveness of heavy minerals to diagenetic dissolution and hydraulic sorting (Gazzi, 1965; Mange and Maurer, 1992; Morton and Hallsworth, 1999).

The aim of the present work, which follows an exemplary rather than exhaustive approach, is to describe and classify detrital heavy mineral assemblages produced in contrasting geodynamic settings within the same conceptual scheme (Fig. 1) as that proposed by Dickinson and coworkers (Dickinson and Suczek, 1979; Dickinson, 1985; Ingersoll, 1990). In order to establish the link between sediment mineralogy and Dickinson's provenance types, we systematically coupled heavy mineral and petrographic analyses on the same sample sets, drawing from numerous case histories carried out with the same analytical methods in key geologic areas (Fig. 2). The cases considered here are all from modern settings, where tectonic processes and geology of source terranes are known in detail, and principally from the arid tropical



*Thick-skinned external belts of collision orogens (Garzanti et al. 2004 a) are not included in this scheme

Fig. 1. Provenance scheme adopted in the present work. Provenance terms introduced by Dickinson and Suczek (1979) and Dickinson (1985) are in bold.

to semiarid Mediterranean climatic belt, where chemical weathering can be considered to be negligible. Detrital signatures can thus be held as primary and used as a reference for provenance interpretation of ancient clastic suites deposited in comparable geodynamic settings.

2. METHODS

2.1. *Analytical Procedures*

In all of our provenance studies we adopted the same standard methods for heavy mineral separation and analysis (Parfenoff et al., 1970). Loose sand samples were either dry or wet sieved. The very fine- to fine-grained sand fraction (63–250 μm) was selected and treated with acetic and oxalic acids to eliminate carbonates and iron oxides, respectively. Heavy minerals were separated with sodium metatungstate (density 2.90 g/cm^3). For each sample, at least 200 points were counted in grain mounts according to the "ribbon-counting" or "Fleet" methods (Mange and Maurer, 1992).

2.2. *The Representation of Heavy Mineral Assemblages*

The potential of heavy mineral studies owes much to the great number of different species found in sediments (some 50 varieties of frequent occurrence). On the other hand, such numerous detrital species cannot be grouped easily into the few basic parameters that can be plotted in binary or ternary diagrams, and there is no

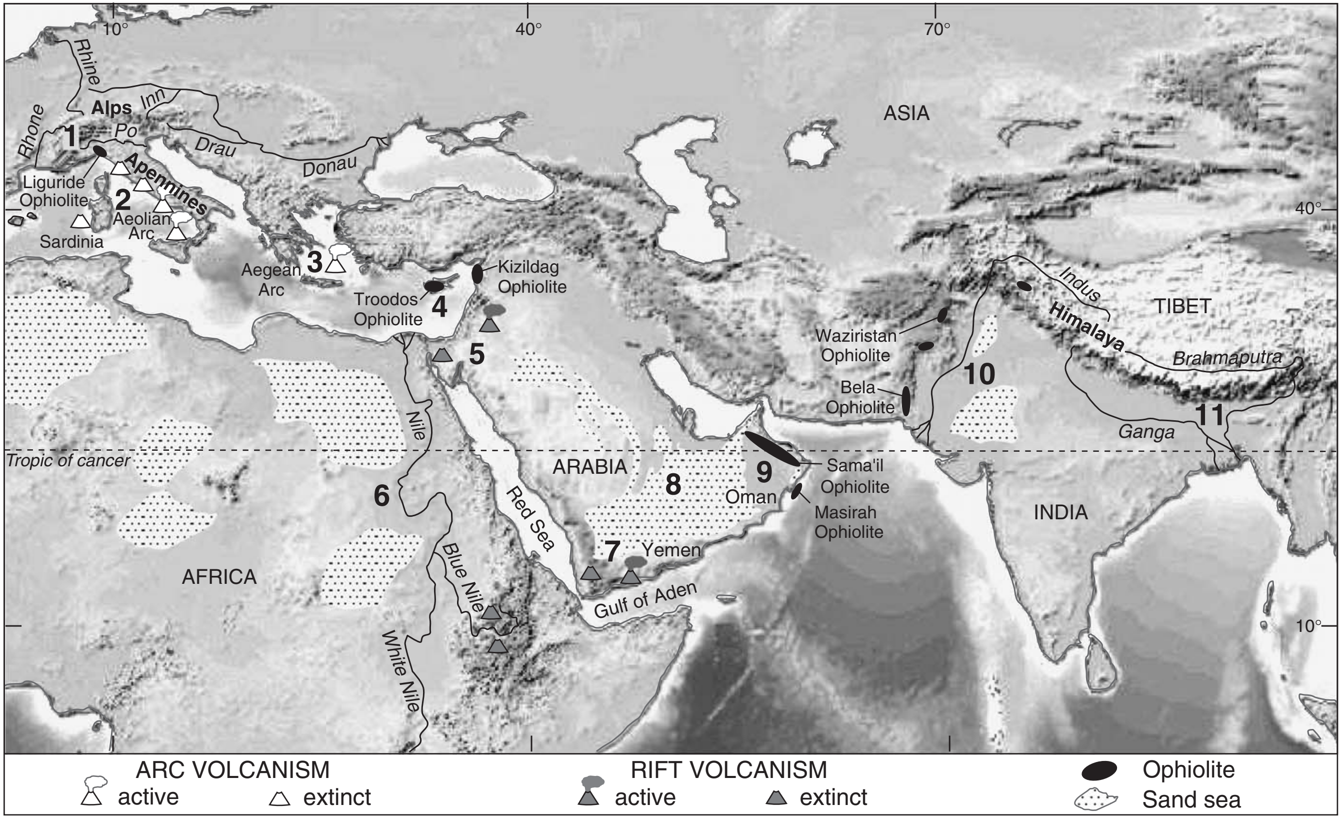


Fig. 2. Map of the key natural laboratories that we used to establish the relationships between plate-tectonic setting and heavy mineral suites of modern sands. For more information on geological framework and full analytical data the reader may refer to the following provenance studies: (1) Western and Central Alps (Garzanti et al., 2004a); (2) Apennines and Tyrrhenian Sea (Garzanti et al., 1998; 2002a); (3) Aegean Arc (Mezzadri and Saccani, 1989); (4) Troodos and Kizildag ophiolites (Garzanti et al., 2000); (5) Levant margin and Northern Red Sea (own unpublished data); (6) Nile river system (Garzanti et al., 2006); (7) Southern Red Sea and Gulf of Aden (Garzanti et al., 2001); (8) Arabian deserts (Garzanti et al., 2003); (9) Sama'il and Masirah ophiolites (Garzanti et al., 2002b); (10) Indus River system (Garzanti et al., 2005); (11) Brahmaputra River system (Garzanti et al., 2004b).

established way to classify heavy minerals for this purpose. Nechaev (1991; see also Nechaev and Isphording, 1993) proposed a three-end-member genetic classification, based on subtle distinctions (e.g., pale-coloured and blue-green amphiboles of the tremolite-actinolite-hornblende series are lumped with epidote and garnet in his MT end-member, diagnostic of mafic metamorphic provenance, whereas green-brown hornblende is grouped with pyroxenes and olivine in his MF end-member, indicative of mafic igneous provenance).

A different approach designed to reduce a great number of species into a limited number of factors is the use of statistical techniques (Imbrie and Van Andel, 1964; Klovan and Imbrie, 1971; Derkachev and Nikolajeva, 2007—this volume; Thamó-Bozsó and Kovács, 2007—this volume). The principal inconvenience of this method is that the identified end-members emerge as artefacts of elusive significance, while the actual direct information provided by the raw data set remains concealed.

2.3. The Ten Key Indices

As a settlement between the need to consider the full spectrum of minerals present in each sample and the ability to compare heavy mineral assemblages of many different samples, we define here 10 relatively homogeneous standard groups of transparent heavy minerals with similar provenance implications (Table 1). These can be either combined further into supergroups (e.g., triangular plots) or split into subgroups, as required by the specific case under scrutiny.

The four most common transparent heavy minerals in modern sands are the amphibole, pyroxene, epidote, and garnet groups. Within the amphibole group, we choose to separate (1) the widely abundant calcic amphiboles (Hb = hornblende) from (2) all of the other species (&A = other amphiboles, including minerals of key significance, such as glaucophane). An obvious distinction, among the pyroxene group, is between (3) clinopyroxenes (CPX, including augite and diopside), and (4) orthopyroxenes (OPX, including enstatite and hypersthene). We group (5) all minerals characterising prehnite-pumpellyite-facies, blueschist-facies, and greenschist-facies metamorphic source rocks as LgM (LgM = "low-grade minerals": epidote, clinozoisite, zoisite, allanite, piemontite, prehnite, pumpellyite, carpholite, lawsonite, chloritoid). (6) Garnet is considered separately (Gt) and (7) species chiefly derived from amphibolite-facies metasediments are categorised as HgM (HgM = "high-grade minerals": staurolite, andalusite, kyanite, and sillimanite). We finally group (8) olivine and spinel, mostly derived from mafic and ultramafic rocks (OS), and (9) the ultrastable minerals zircon, tourmaline, and rutile (ZTR), which tend to form a residual concentrate in both recycled modern sands and ancient sandstones affected by diagenesis (Hubert, 1962); (10) all remaining transparent heavy minerals are combined in the last index (T&, including the titanium minerals sphene, anatase, and brookite, as well as monazite, xenotime, apatite, and barite, found in traces in felsic igneous or sedimentary source rocks).

These 10 indices are conventionally tabulated in the following order that mainly represents petrogenetic suites: ultrastable to relatively stable minerals, mainly derived from sedimentary and felsic igneous source rocks (ZTR, T&), minerals chiefly provided by low- to high-grade metamorphic source rocks (LgM, Gt, HgM), and amphiboles (Hb, &A), pyroxenes (CPX, OPX), olivine and spinel (OS) largely

Table 1. Recalculated key indices for a synthetic representation of heavy mineral assemblages

HMC	Heavy mineral concentration index (Garzanti and Andò, 2007—this volume)
% Transparent	Identified transparent heavy minerals/total heavy minerals
% Opaque	Opaque heavy minerals/total heavy minerals
% Turbid	Altered unidentified heavy minerals/total heavy minerals
ZTR	Ultrastable minerals (Z = zircon; T = tourmaline; R = rutile)
T&	Titanium minerals (sphene, anatase, brookite) + others (e.g., apatite, monazite, barite)
LgM	Low-grade metamorphic minerals (e.g., epidote-group, chloritoid, carpholite, lawsonite)
Gt	Garnet
HgM	High-grade metasedimentary minerals (staurolite, andalusite, kyanite, sillimanite)
Hb	Hornblende
&A	Other amphiboles (including glaucophane, tremolite, actinolite)
CPX	Clinopyroxenes
OPX	Orthopyroxenes
OS	Olivine (O) + spinel (S)
HCI = (1/3 green hornblende + 2/3 green-brown hornblende + brown hornblende)/hornblende × 100	
MMI = (1/3 staurolite + 2/3 kyanite + sillimanite)/(chloritoid + staurolite + kyanite + sillimanite) × 100	
% Rounded	Rounded transparent heavy minerals/total transparent heavy minerals

supplied by intermediate, mafic, and ultramafic igneous or meta-igneous source rocks. It must be noted that the LgM and HgM categories are not labelled rigorously (e.g., epidote, here included in the LgM pole, may persist well into medium-grade metamorphism: Winkler, 1976). Although high-pressure/low-temperature metamorphic minerals (e.g., carpholite, lawsonite, glaucophane) have a great diagnostic significance in provenance studies (e.g., Mange-Rajetzky and Oberhänsli, 1982), their separation in a distinct group is impractical because it requires distinctions that cannot be done under the microscope (e.g., Mg- vs. Fe-rich chloritoid) and a rather arbitrary split of the ‘‘other amphiboles’’ category.

2.4. *Other Useful Indices*

The basic string of 10 primary compositional parameters defined above can be supplemented by a set of secondary parameters providing detailed and crucial information. These may include concentration parameters (HMC, tHMC, and SRD parameters defined in Garzanti and Andò, 2007—this volume), as well as ratio parameters based on heavy mineral species either with highest density and chemical stability (in order to reveal the effects of hydraulic sorting and diagenetic dissolution;

% opaque, % ultradense, % ZR defined in Garzanti and Andò, 2007—this volume), or with similar density and chemical stability and therefore characterised by similar behaviour during transport, deposition, and diagenesis (in order to reveal provenance specifically in sandstones modified by diagenesis: Morton and Hallsworth, 1994).

Other parameters, quite helpful in the study of orogenic sediments to estimate the average metamorphic grade of source rocks, are the hornblende colour index (HCI: Garzanti et al., 2004a) and the metasedimentary minerals index (MMI). The latter is defined here as the weighted sum of the relative percentage of the four index minerals most commonly found in low- to high-grade metasediments (chloritoid, staurolite, kyanite, and sillimanite; Table 1). MMI and HCI indices vary from 0 in greenschist-facies to lowermost amphibolite-facies rocks (yielding chloritoid and blue-green amphibole), to 100 in granulite-facies rocks (yielding sillimanite and brown hornblende).

3. CONTINENTAL BLOCK PROVENANCE AND HEAVY MINERAL SUITES

Quartzofeldspathic to quartzose sands of "Continental Block Provenance" ("Uplifted Basement" to "Craton Interior" subprovenances of Dickinson and Suczek, 1979) are deposited along young continental rifts and mature passive continental margins, respectively. The source of detritus is the continental crust, either disrupted by extensional tectonic processes and exposed along rift-shoulder escarpments, or representing the backbone of vast but low-relief cratonic areas.

3.1. Rifted-Margin Provenances

The most spectacular modern example of an active rift is the Dead Sea-Red Sea-Gulf of Aden system. Successive evolutionary stages are documented from north to south, from continental wrenching along the Levant fault, to diffuse extension in the northern Red Sea, to initial spreading in the southern Red Sea, to full spreading along the Sheba Ridge (Cochran, 1981, 1983; Rihm and Henke, 1998).

Heavy mineral suites in volcaniclastic, to sedimentaclastic, to basementaclastic detritus produced along this divergent plate margin from Syria to Oman depend directly and primarily on the intensity of tectonic and magmatic activity in the source terrane (Garzanti et al., 2001, 2003). Three provenance end-members are recognised (Table 2).

Along rift segments associated with prominent volcanic activity, as in the southernmost Red Sea where extensive magmatism controlled by the Afar Plume began in the Oligocene (Davison et al., 1994; Ukstins et al., 2002), heavy mineral suites are invariably dominated by lilac-brown and subordinately green augite, locally associated with olivine and brown hornblende ("Volcanic Rifted Margin Provenance").

Rift segments where volcanic activity is minor are characterised either by continuous exposures of pre-rift sedimentary successions ("Undissected Rift Shoulder subprovenance") or by extensive outcrops of the underlying basement rocks ("Dissected Rift Shoulder subprovenance"), depending on pre-rift stratigraphy as well as on the intensity and duration of uplift associated with tectonic extension. Quartzose

Table 2. Modern heavy mineral suites of "Continental Block Provenance"

	No.	HMC	% t_{HM}	% op_{HM}	% tu_{HM}	ZTR	T&	LgM	Gt	HgM	Hb	&A	CPX	OPX	OS	HCI	MMI	% Rounded
Volcanic rifted margin provenance																		
Levant Margin (Harrat Ash Shams)	3	21	75	16	10	0	0	1	0	0	0	0	79	0	20	n.d.	n.d.	0
Gulf of Aden (Shuqrah)	1	32	91	1	8	0	0	0	0	0	8	0	75	0	17	100	n.d.	0
Southern Red Sea (Ethiopian Traps)	2	36	74	22	4	0	0	11	0	0	3	0	79	1	5	n.d.	n.d.	0
Southern Red Sea (Yemen Traps)	11	15	74	18	9	0	1	8	0	0	6	0	84	1	0	n.d.	n.d.	2
Undissected rift shoulder provenance																		
Levant Margin	2	0.3	40	9	51	80	5	2	1	0	9	0	4	0	0	15	n.d.	19
Northern Red Sea	3	1	32	27	41	30	6	20	3	6	19	1	15	0	0	31	33	22
Gulf of Aden	8	1	52	39	9	24	1	27	15	1	24	1	4	2	1	27	35	23
Dissected rift shoulder provenance																		
Northern Red Sea	11	9	55	27	18	6	9	12	1	1	53	1	16	0	0	11	39	13
Southern Red Sea	4	12	92	5	3	1	2	17	1	0	62	2	14	0	0	9	n.d.	8
Gulf of Aden	10	13	87	8	5	2	2	11	2	1	72	2	5	3	1	11	34	1
Cratonic provenance																		
Northeastern Africa	8	1	35	41	24	30	2	29	9	14	10	0	3	1	0	7	43	39
Arabia	12	0.9	69	18	13	7	0	49	15	1	17	2	5	2	1	38	28	20
Northern India	7	5	75	11	14	14	4	14	11	2	47	2	5	1	0	16	62	5

Note: %Transparent = %t_{HM}, %Opaque = %op_{HM}, %Turbib = %tu_{HM}.

to carbonaticlastic sands of “Undissected Rift Shoulder subprovenance” have limited amount and low-diversity heavy mineral suites with commonly rounded ultrastable grains, testifying to extensive recycling of pre-rift strata. Quartzofeldspathic sands of “Dissected Rift Shoulder subprovenance” yield, by contrast, abundant heavy minerals with assemblages that are dominated by mainly blue-green to green-brown hornblende grains from amphibolite-facies basement rocks.

As typically occurs in nature, all intermediate cases exist, both between “Volcanic Rifted Margin” and “Rift Shoulder” Provenances, and between “Undissected Rift Shoulder” and “Dissected Rift Shoulder” subprovenances (Fig. 3). Because heavy minerals are supplied in much greater abundance by volcanic or basement rocks than by sedimentary successions, sands of “Transitional Rifted-Margin” or “Transitional Rift Shoulder” subprovenances are typically poor in heavy minerals (with suites dominated by augite or hornblende, respectively), and contain rounded ultrastable minerals only in subordinate quantities. In areas where upper crustal levels are widely preserved within basement complexes, modern sands may include abundant to dominant epidote (e.g., detritus from the shallow roots of ancient magmatic arcs) or garnet and staurolite from lower-amphibolite-facies metasediments.

3.2. Craton Provenance

Heavy minerals of quartzose to quartzofeldspathic sands derived from cratonic shields are comparable with “Rift Shoulder” suites (Fig. 3). A low heavy mineral content with commonly rounded ultrastables, epidote, garnet, staurolite, and kyanite characterises areas where upper-crustal basement levels and cover strata are widely preserved (“Undissected Craton subprovenance”). Instead, deeply eroded shield areas where amphibolite-facies middle-crustal levels are extensively exposed (“Dissected Craton subprovenance”) supply abundant heavy minerals, with assemblages dominated by mainly blue-green to green and brown hornblende.

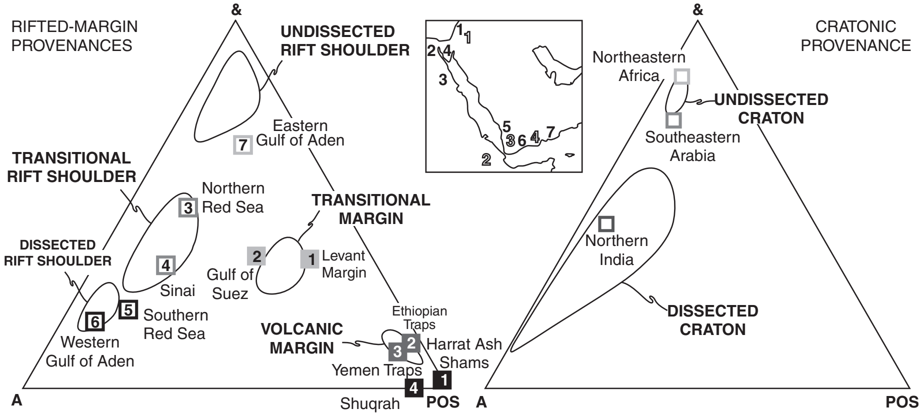


Fig. 3. “Continental Block Provenance” and heavy mineral suites. & = all transparent heavy minerals not included in the other two poles. A = Hb + &A = total amphiboles. POS = CPX + OPX + OS = pyroxenes, olivine, and spinel. Parameters defined in Table 1. 90% confidence regions about the mean calculated after Weltje (2002).

4. MAGMATIC ARC PROVENANCE AND HEAVY MINERAL SUITES

Lithofeldspathic detritus derived from volcanic arcs is typified by pyroxene-dominated heavy mineral assemblages (“Undissected Arc subprovenance”). These include only a limited number of diagnostic species, which display the narrow range of chemical compositions typical of orogenic magmatism (Ewart, 1976). The two dominant minerals are augite, found in the vast majority of orogenic lavas, and hypersthene, absent in basalts but widespread in andesites. Olivine, ubiquitous in basalts, is found even in felsic andesites. Hornblende is common in medium- to high-K felsic andesites and dacites, frequently associated with biotite. The ratio of orthopyroxene to clinopyroxene phenocrysts typically increases with increasing silica contents, and orthopyroxene is generally antipathic with both olivine and hornblende (Gill, 1981). Other clinopyroxenes are pigeonite (tholeiitic andesites lacking olivine) and clinoenstatite (boninites). Magnetite (relatively Ti-poor titanomagnetite) is the dominant opaque mineral. Garnet and spinel (locally occurring as inclusions in olivine phenocrysts) are infrequent.

Quartzofeldspathic detritus from calc-alkaline batholiths, representing the remnants of eroded arcs, is hornblende-dominated (Fig. 4; “Dissected Arc subprovenance”). Mixed assemblages, including augite and hypersthene from volcanic covers, associated in various proportions with hornblende and subordinate epidote from the plutonic roots and metamorphic wallrocks of the arc massif (“Transitional Arc subprovenance”) are frequently found in Circum-Pacific sands. These range from the western Pacific (Murdmaa et al., 1980; Sato, 1981; Nechaev, 1991) to the Bering Sea and Gulf of Alaska (Knebel and Creager, 1974; Slatt and Piper, 1974; Stewart, 1976), to offshore North America (Scheidegger et al., 1973; Nechaev and Isphording, 1993; Zuffa et al., 2000), Middle America (Ross, 1971; Bachman and Leggett, 1982; Enkeboll, 1982; Prasad and Hesse, 1982), South America (Thornburg and Kulm, 1987), and as far as the Antarctic Peninsula (Peters and Hollister, 1976). The correspondence with Dickinson’s provenance fields was established on petrographic information either available on the same sample sets (Stewart, 1976; Thornburg and Kulm, 1987; Zuffa et al., 2000) or found in Marsaglia and Ingersoll (1992).

4.1. *Modern Sands from Circum-Pacific Volcanic Arcs*

Heavy mineral assemblages in Circum-Pacific lithofeldspathic volcaniclastic sands (Dickinson, 1982; Marsaglia and Ingersoll, 1992) have a variable clinopyroxene/orthopyroxene ratio (Table 3). Clinopyroxene dominates in beach placers of the Tonga islands, where olivine is locally present and hornblende invariably absent (Dye and Dickinson, 1996). Augite-olivine and augite-hypersthene assemblages characterise turbidites of the West Philippine Basin and Parece Vela to Mariana basins, respectively (Nechaev, 1991). Turbidites of the Izu-Bonin Arc display a temporal trend from abundant augite with common orthopyroxenes and minor hornblende in the Oligocene, to prevalent orthopyroxenes, augite, and locally olivine in the Pleistocene (Fujioka and Saito, 1992). Orthopyroxene prevails in beach sands of northern Hokkaido (Noda, 2005) and Kamchatcka. Hornblende is common in many Solomons and some Bismarck and Vanuatu (New Hebrides) sands (W.R. Dickinson, Written Communication, 2004).

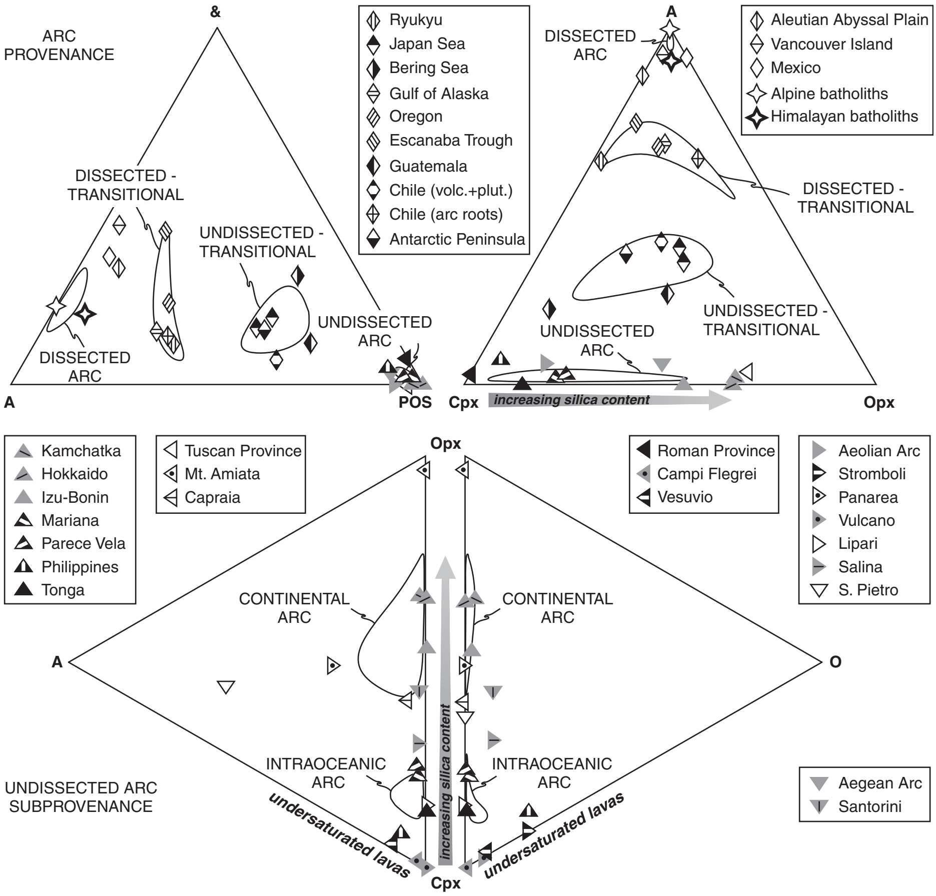


Fig. 4. "Magmatic Arc Provenance" and heavy mineral suites. The double triangle below discriminates between intraoceanic (largely basalts and basaltic andesites) and continental (commonly felsic andesites to rhyolites) "Undissected Arc subprovenance". Modern beach sands from Miocene peralkaline rhyolites of southwestern Sardinia (S. Pietro Island) include sodic amphiboles and pyroxenes (abundant arfvedsonite, minor aegirine). & = all transparent heavy minerals not included in the other two poles. A = Hb + &A = total amphiboles. POS = CPX + OPX + OS = pyroxenes, olivine, and spinel. Parameters defined in Table 1. 90% confidence regions about the mean calculated after Weltje (2002). Data for Roman Province and Aegean Arc mostly from Gandolfi and Paganelli (1984) and Mezzadri and Saccani (1989), respectively. Data for Circum-Pacific arcs after various sources cited in text.

4.2. *Modern Sands from Mediterranean Volcanic Arcs*

River and beach sands from silica-saturated felsic products of the Tuscan Province (central Italy) are characterised by yellow-green hypersthene (Serri et al., 1993), which is either dominant (Mt. Amiata) or subordinate to green augite and associated with oxyhornblende and biotite (Capraia Island). Detritus from slightly to strongly undersaturated potassic to ultrapotassic lavas of the Roman Province (central and southern Italy) are dominated by green augite, with minor hornblende,

Table 3. Modern heavy mineral suites of "Magmatic Arc Provenance"

	No.	HMC	%t_{HM}	%op_{HM}	%tu_{HM}	ZTR	T&	LgM	Gt	HgM	Hb	&A	CPX	OPX	OS	HCI	MMI	% Rounded
Undissected magmatic arc provenance																		
Mediterranean Arcs																		
Tuscan Province	2	6	86	3	11	0	0	0	1	0	2	0	32	65	0	100	n.d.	0
Roman Province	57	32	90	5	5	0	0	1	3	0	3	0	90	0	2	79	n.d.	0
Aeolian Arc	11	47	86	5	9	0	0	0	0	0	6	0	73	15	6	n.d.	n.d.	0
Aegean Arc	38	22	84	2	13	0	1	2	0	1	2	4	46	43	0	100	n.d.	1
Pacific Arcs																		
Tonga	7	91	n.d.	11	n.d.	0	0	0	0	0	0	0	86	14	Trace	n.d.	n.d.	n.d.
Philippines	9	n.d.	n.d.	25	n.d.	0	1	4	0	0	6	0	69	4	16	n.d.	n.d.	n.d.
Parece Vela	21	n.d.	n.d.	25	n.d.	0	0	2	0	0	3	0	72	23	0	n.d.	n.d.	n.d.
Mariana	47	n.d.	n.d.	18	n.d.	0	0	1	0	0	2	0	75	21	0	n.d.	n.d.	n.d.
Izu-Bonin	99	n.d.	n.d.	n.d.	n.d.	0	0	0	0	0	0	0	46	51	2	n.d.	n.d.	n.d.
Hokkaido	28	20	n.d.	15	n.d.	0	0	0	0	0	0	0	35	65	0	n.d.	n.d.	n.d.
Kamchatka	1	83	67	25	8	0	0	0	0	0	2	0	32	62	3	n.d.	n.d.	1
Dissected magmatic arc provenance																		
Alpine batholiths	5	14	85	12	2	3	4	15	0	0	78	0	0	0	0	7	n.d.	0
Himalayan batholiths	5	25	80	8	12	1	3	16	0	0	69	3	4	4	0	16	n.d.	0

Note: Data for Roman Province and Aegean Arc mostly from Gandolfi and Paganelli (1984) and Mezzadri and Saccani (1989), respectively. Data for Circum-Pacific arcs after various sources cited in text.

%Transparent = %t_{HM}, %Opaque = %op_{HM}, %Turbib = %tu_{HM}.

oxyhornblende, olivine, chrome spinel, and locally significant melanite (Gt up to 15) (Gandolfi and Paganelli, 1984; Peccerillo, 1985; Garzanti et al., 2002a).

Green augite is widespread in the heavy mineral-rich beach sands of the Aeolian Arc. High-K basalts and basaltic andesites of Stromboli Island also supply abundant olivine, whereas felsic andesites, dacites, and rhyodacites of Panarea Island (Calanchi et al., 2002) also contribute abundant yellow-green hypersthene and dark-brown hornblende. Rhyolite-derived sands on Lipari Island contain fewer heavy minerals. Detrital green to pale-green clinopyroxene and hypersthene are largely xenocrysts, derived from more mafic enclaves and pumices within felsic lava domes and pyroclastic deposits (Gioncada et al., 2003). Beach to turbidite sands derived from the Aegean Arc are dominated by augite and hypersthene, with minor oxyhornblende and trace olivine (Mezzadri and Saccani, 1989).

4.3. Modern Sands from Alpine and Himalayan Batholiths

The deeply eroded roots of ancient magmatic arcs, representing the Cretaceous-Eocene Asian active margin of Neotethys, are exposed all along the Indus-Tsangpo suture from Pakistan to Burma (Gansser, 1980). Quartzofeldspathic detritus from these Transhimalayan batholiths include dominant blue-green to more rarely green and brown hornblende, associated with epidote, clinopyroxenes, hypersthene, and sphene (Garzanti et al., 2004b, 2005). Abundant epidote and minor actinolite are supplied locally by greenschist-facies metamorphosed arc rocks. Similar signatures, with dominant blue-green to more rarely green and brown hornblende, along with epidote, minor sphene or zircon, and trace monazite, characterise quartzofeldspathic detritus from Tertiary Alpine plutons (Bregaglia, Adamello).

5. OROGENIC PROVENANCE AND HEAVY MINERAL SUITES

Orogenic provenance is a complex subject, difficult to deal with in brief because each thrust belt has its own tectonic style, peculiar rock assemblage, and stacking pattern. Moreover, orogenic belts commonly incorporate remnants of ophiolitic complexes and magmatic arcs, eroded to various levels along the suture zone (the latter contributing detritus of "Magmatic Arc Provenance"), and basement slivers overlain by passive-margin strata along the external flanks (contributing detritus of "Continental Block Provenance").

Different classes of orogens, defined as allochthonous tectonic prisms formed in the hangingwall of subducting continental crust, exist. They include Alpine or Himalayan-type thick-skinned collision orogens, Oman-type ophiolite-capped obduction orogens, and Apennine-type thin-skinned thrust belts (Cawood, 1991; Michard et al., 1991; Doglioni et al., 1999; Garzanti et al., 2002b).

5.1. Modern Sands from the Alpine Collision Orogen

The Alps are a double-vergent thick-skinned orogen formed by continental collision (Pfiffner et al., 1997). Alpine calc-alkaline magmatic rocks are confined to tonalite-granodiorite plutons and associated andesite dike-swarms intruded along the

Periadriatic Zone (e.g., Bregaglia, Adamello). The axial metamorphic backbone of the orogen incorporates remnants of the thinned distal edges of collided continental margins and intervening oceanic rocks, which underwent attempted subduction and high-pressure metamorphism in the early orogenic (Late Cretaceous-Eocene) stage (Dal Piaz, 1999; Gebauer, 1999). The external belts on both sides of the orogen (Southalpine and Helvetic-Dauphinois Zones) include inverted listric wedges of European and Adriatic basements along with their covers that experienced negligible to lower-amphibolite-facies Tertiary metamorphism (Frey et al., 1999).

Heavy mineral suites of Alpine-derived modern sediments are primarily related to structural level of source rocks (Garzanti et al., 2004a). Quartzofeldspathic gneissiclastic detritus derived from the amphibolite-facies Lepontine Dome of the Central Alps include abundant hornblende. The abundance of hornblende grains in sands carried by local streams increases from the periphery to the core of the dome, while their most frequent colour changes from exclusively blue-green to green, green-brown, and locally brown, reflecting compositional changes with increasing metamorphic grade (Miyashiro, 1972, p. 254). Epidote-group minerals, actinolite, or garnet are most abundant in sands carried by rivers draining the periphery (or partly outside) of the dome. Pyroxenes, staurolite, kyanite, and sillimanite are invariably subordinate; olivine occurs locally.

Quartzolithic metamorphiclastic detritus derived from the high-pressure metamorphic nappes exposed extensively in the Western Alps, as well as in the Engadine and Tauern windows of the Eastern Alps, contain dominant epidote, largely reflecting extensive retrogression at greenschist facies. High-pressure minerals include carpholite, zoisite, Mg-chloritoid, glaucophane, and Mg- and Ca-rich almandine garnet. Meta-ophiolites supply heavy mineral-rich sediment with amphiboles (actinolite, blue-green barroisitic hornblende, glaucophane), and minor pyroxenes. Continental basements contribute abundant garnet and, locally, even sillimanite, hypersthene, and brown hornblende from pre-Alpine granulite-facies relics (e.g., Dent Blanche Nappe). Metasedimentary covers provide mostly turbid grains and a few ultrastable heavy minerals.

Lithoquartzose sedimentaclastic detritus derived from sedimentary thrust sheets (Liguride remnant-ocean turbidites in the Western Alps, Austroalpine platform carbonates and clastics in the Eastern Alps) are very poor in heavy minerals, which largely consist of recycled grains (ultrastables, garnet, staurolite). Oceanic turbidites also supply amphiboles, pyroxenes, and chrome spinel. Reactivated basement slivers of the external belts contribute heavy mineral suites similar to those contained in the sands of "Dissected Continental Block" subprovenances.

5.2. *Modern Sands from the Himalayan Collision Orogen*

The Himalaya is the paradigm of a thick-skinned belt produced by continent–continent collision (Hodges, 2000). In contrast to the Alps, the Himalaya includes a passive margin on the Indian side (North Himalaya, Tethys Himalaya, Greater Himalaya, and Lesser Himalaya zones; Le Fort, 1996) and a fully developed active margin on the Asian side (Transhimalaya zone), separated by the Indus-Tsangpo suture (Gansser, 1980). Only the two largest fluvial systems, the Indus and the Tsangpo-Brahmaputra, drain the Asian active margin. Their sands contain high proportions of heavy minerals, dominated by blue-green hornblende associated with epidote, garnet, and kyanite. Such a signature is unique with respect to any other major river sourced in the Himalaya or in the Alps (Fig. 5). Although it partly reflects contributions from Transhimalayan batholiths, it is largely related to another peculiarity of the two systems, that have about a fourth of their sediment load produced by super-fast erosion of the western and eastern Himalayan syntaxes (Garzanti et al., 2004b, 2005). Upper-amphibolite-facies mid-crustal levels are here unroofed at the core of crustal-scale antiforms, at rates up to 5 mm per year (Burg et al., 1998; Rolland et al., 2001). Contributions from ophiolitic mélanges and volcaniclastic suites exposed along oceanic suture zones (pyroxenes, olivine, chrome spinel, glaucophane) are negligible. All of the other major Himalayan rivers, including the Ganga, chiefly drain the Greater and Lesser Himalaya zones along the southern flank of the range. Their load is significantly poorer in heavy minerals, and comprise, in order of abundance, blue-green to green and locally brown hornblende, garnet, epidote, clinopyroxene, kyanite, and sillimanite (Table 4).

5.3. Modern Sands from Oman-Type Obduction Orogens

The best-studied obducted ophiolite belt on Earth is spectacularly exposed in northern Oman, where a thick-skinned thrust belt was generated by attempted subduction of the eastern Arabian continental platform underneath an oceanic plate (Glennie et al., 1974; Searle and Cox, 1999). Modern sands produced in such a geodynamic setting contain abundant mafic and ultramafic minerals, derived from the obducted oceanic lithosphere (Table 4; Garzanti et al., 2000, 2002b).

Mantle harzburgites supply enstatitic orthopyroxene, associated with olivine and minor chrome spinel. Olivine and chrome spinel are subordinate for contrasting

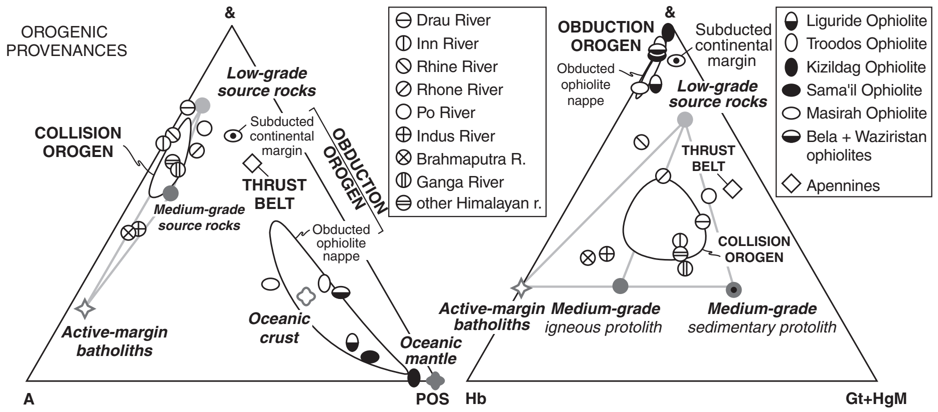


Fig. 5. "Orogenic Provenance" and heavy mineral suites. & = all transparent heavy minerals not included in the other two poles. A = Hb + &A = total amphiboles. POS = CPX + OPX + OS = pyroxenes, olivine, and spinel. Parameters defined in Table 1. 90% confidence regions about the mean calculated after Weltje (2002). Data for Po delta and Internal Liguride units include analyses by Gazzi et al. (1973) and Gandolfi and Paganelli (1975). End-member compositions calculated after selected data from provenance studies listed in Fig. 2.

Table 4. Modern heavy mineral suites of "Orogenic Provenance"

	No.	HMC	%t_{HM}	%op_{HM}	%tu_{HM}	ZTR	T&	LgM	Gt	HgM	Hb	&A	CPX	OPX	OS	HCI	MMI	% Rounded
Collision orogen provenance																		
Himalaya																		
Indus River	12	12	84	7	9	2	2	24	13	3	48	2	3	3	0	12	61	0
Brahmaputra River	8	11	89	6	6	3	2	25	11	1	53	2	3	1	0	8	73	0
Ganga River	12	4	88	5	7	7	2	14	28	9	31	2	6	0	0	9	71	1
Other rivers	18	4	83	8	9	7	2	19	28	6	30	2	5	0	0	13	67	1
Alps																		
Po River	17	11	77	12	11	3	2	33	31	3	15	7	4	3	0	38	47	0
Rhone River	4	4	61	14	25	6	2	39	18	1	23	3	9	0	0	25	61	1
Rhine River	1	3	36	20	44	9	1	51	9	0	24	7	1	0	0	6	n.d.	0
Inn River	3	3	71	12	17	3	1	30	26	6	28	5	0	0	0	3	32	0
Drau River	5	6	78	6	15	3	2	37	33	2	20	1	1	0	0	6	32	0
Obduction orogen provenance																		
Obducted ophiolite nappe																		
Internal Liguride	21	4	67	11	22	1	1	6	4	0	12	3	65	5	4	77	17	0
Troodos	7	20	87	3	9	0	0	27	0	0	6	9	53	5	1	28	n.d.	1
Bela and Waziristan	2	18	65	6	29	1	0	24	0	0	8	3	50	9	6	25	n.d.	0
Masirah	7	24	70	11	19	1	0	24	1	0	17	10	42	2	2	30	n.d.	3
Sama'il	24	32	80	9	11	0	0	6	0	0	8	5	20	47	14	57	n.d.	0
Kizildag	5	30	92	1	6	0	0	1	0	0	2	3	20	42	32	19	n.d.	2
Subducted continental margin units																		
Saih Hatat	4	31	43	26	31	5	0	58	5	0	4	12	10	5	0	n.d.	n.d.	1
Thrust belt provenance																		
Apennines	93	2	59	9	32	5	3	17	35	3	8	6	17	5	2	n.d.	36	n.d.

Note: Data for Po delta and Internal Liguride units include analyses by Gazzi et al. (1973) and Gandolfi and Paganelli (1975).
%Transparent = %t_{HM}, %Opaque = %op_{HM}, %Turbib = %tu_{HM}.

reasons (Garzanti and Andò, 2007—this volume). The former, abundant in the source rocks but chemically very unstable, is selectively destroyed by serpentinization before, during, and after obduction (Wenner and Taylor, 1974) or by weathering in sedimentary environments. The latter, chemically stable but sparse in the source rocks, is concentrated only in detritus derived from very-extensively serpentinised peridotites, or by sedimentary processes including intense weathering in equatorial climates, hydraulic sorting, and recycling.

Lower-crustal gabbroic rocks release not only abundant pyroxenes, including diopside or diallage but also significant green-pink hypersthene from noritic gabbros generated in supra-subduction settings (Lachize et al., 1996). Subordinate hornblende is chiefly derived from isotropic high-level gabbros. Sheeted-dyke complexes, intensely altered during oceanic metamorphism, supply diopsidic clinopyroxenes, actinolitic amphiboles, locally abundant epidote, and significant hypersthene in supra-subduction settings. Lavas contribute dominantly pyroxenes (green to brown augite, along with yellow-green orthopyroxene in supra-subduction settings).

When and where erosion bites into the continental roots of the orogen beneath the ophiolite nappe, detritus displays features similar to "Collision Orogen Provenance". Modern sands derived from blueschist- to eclogite-facies subducted remnants of the Arabian outer continental margin contain epidote-dominated assemblages with carpholite, lawsonite, glaucophane, and garnet, which is comparable with those derived from high-pressure units of the Western Alps (Garzanti et al., 2004a).

5.4. Modern Sands from Apennine-Type Thrust Belts

Thin-skinned thrust belts, chiefly consisting of allochtonous passive-continental-margin successions, provide few and largely recycled heavy minerals. Unroofed metamorphic complexes may locally supply a few low-grade or high-pressure minerals (e.g., epidote, chloritoid).

Heavy mineral suites of Apennine-derived sands largely include clinopyroxenes from either offscraped ophiolites (diallage; Northern Apennines) or Quaternary volcanic rocks (green augite; Tyrrhenian coast). Garnet, epidote, and minor staurolite and kyanite are recycled from extensively exposed foredeep turbidites, ultimately fed from the adjacent Alpine thick-skinned orogen (Garzanti et al., 2002a).

6. CONCLUSIONS

High-resolution heavy mineral analysis is an extremely powerful tool in provenance studies. The great number of mineral species and varieties found in modern sediments, not modified by diagenesis, allow us to obtain a wealth of detailed information on source areas, augmenting that provided by the petrographic analysis of bulk sediment.

We follow here the model of Dickinson (1985), which identifies three main provenances of terrigenous sediments. Sources of detritus in "Continental Block Provenance" are variously dissected rifted margins or cratonic shields, located along divergent plate boundaries or in intraplate settings and not associated with subduction zones. Sources of detritus in "Magmatic Arc Provenance" are volcanic and volcano-plutonic belts, formed in the hanging-wall of an oceanic subduction zone. Sources of detritus in "Orogenic Provenance" are thick-skinned collision or obduction orogens and thin-skinned thrust belts, chiefly consisting of metamorphic complexes, oceanic sequences, and passive-margin successions tectonically stacked in the hanging-wall of a continental subduction zone.

Major provenance types cannot be discriminated just by the simple acritical use of one standardised binary or ternary diagram. All of the evidence provided by detrital assemblages must be given full consideration. Subtle distinctions, such as those based on colour of amphibole and pyroxene grains (Nechaev and Isphording, 1993; Garzanti et al., 2004a), are crucial in differentiating magmatic or metamorphic assemblages exposed along rifted margins, magmatic arcs, and collision or obduction orogens.

Through a series of modern case studies, we highlighted the strict relationships that exist between plate-tectonic setting and both bulk-framework composition and heavy mineral assemblages of terrigenous sediments, and showed how the conceptual models, proposed and refined by Dickinson and co-workers since the 1970s (Dickinson and Suczek, 1979), can be integrated and extended to provenance diagnosis of heavy mineral suites. A precise and accurate discrimination of geodynamic processes, character of magmatic activity, depth of erosion level, metamorphic grade, and original nature of protoliths eroded in the source terrane can thus be achieved.

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REFERENCES

Bachman, S.B., Leggett, J.K., 1982. Petrology of Middle America trench and trench-slope sands, Guerrero margin, Mexico. In: Initial Report of the Deep Sea Drilling Project, vol. 66, pp. 429–436.

Bathia, M.R., 1985. Plate tectonics and geochemical composition of sandstones. Journal of Geology 91, 611–627.

Burg, J.-P., Nievergelt, P., Oberli, F., Seward, D., Davy, P., Maurin, J.-C., Diao, Z., Meier, M., 1998. The Namche Barwa syntaxis: evidence for exhumation related to compressional crustal folding. Journal of Asian Earth Science 16, 239–252.

Calanchi, N., Peccerillo, A., Tranne, C.A., Lucchini, F., Rossi, P.L., Kempton, P., Barbieri, M., Wu, T.W., 2002. Petrology and geochemistry of volcanic rocks from the island of Panarea: implications for mantle evolution beneath the Aeolian island arc (southern Tyrrhenian sea). Journal of Volcanology and Geothermal Research 115, 367–395.

Cawood, P.A., 1991. Processes of ophiolite emplacement in Oman and Newfoundland. In: Peters, T., Nicolas, A., Coleman, R.G. (Eds.), Ophiolite Genesis and Evolution of Oceanic Lithosphere. Kluwer, Dordrecht, pp. 501–516.

Cochran, J.R., 1981. The Gulf of Aden: structure and evolution of a young ocean basin and continental margin. Journal of Geophysical Research 86, 263–287.

Cochran, J.R., 1983. A model for development of Red Sea. American Association of Petroleum Geologists Bulletin 67, 41–69.

Dal Piaz, G.V., 1999. Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys. Memorie della Società Geologica Italiana 51, 155–176.

Davison, I., Al-Kadasi, M., Al-Khirbash, S., Al-Subbary, A., Baker, J., Blakey, S., Bosence, D., Dart, C., Heaton, R., McClay, K., Menzies, M., Nichols, G., Owen, L., Yelland, A., 1994. Geological evolution of the southeastern Red Sea rift margin, Republic of Yemen. Geological Society of America Bulletin 106, 1474–1493.

Derkachev, A.N., Nikolajeva, N.A., 2007. Multivariate analysis of heavy mineral assemblages of sediments from the marginal seas of the Western Pacific. In: Mange, M.A., Wright, D.T. (Eds.), Heavy Minerals in Use. Developments in Sedimentology (this volume).

Dickinson, W.R., 1974. Plate tectonics and sedimentation. In: Dickinson, W.R. (Ed.), Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists. Special Publication 22, 1–27.

Dickinson, W.R., 1982. Composition of sandstones in Circum-Pacific subduction complexes and fore-arc basins. American Association of Petroleum Geologists Bulletin 66, 121–137.

Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), Provenance of Arenites, Reidel, Dordrecht, NATO ASI Series 148, pp. 333–361.

Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstone composition. American Association of Petroleum Geologists Bulletin 63, 2164–2172.

Doglioni, C., Harabaglia, P., Merlini, S., Mongelli, F., Peccerillo, A., Piromallo, C., 1999. Orogens and slabs vs. their direction of subduction. Earth Science Reviews 45, 167–208.

Dye, T.S., Dickinson, W.R., 1996. Sources of sand tempers in Prehistoric Tongan pottery. Geoarchaeology 11, 141–164.

Enkeboll, R.H., 1982. Petrology and provenance of sands and gravels from the Middle America Trench and trench slope, southwestern Mexico and Guatemala. Initial Report of the Deep Sea Drilling Project 66, 521–530.

Ewart, A., 1976. Mineralogy and chemistry of modern orogenic lavas—some statistics and implications. Earth and Planetary Science Letters 31, 417–432.

Frey, M., Desmons, J., Neubauer, F., 1999. The new metamorphic map of the Alps. Schweizerische Mineralogische und Petrographische Mitteilungen 79, 1–209.

Fujioka, K., Saito, S., 1992. Composition of heavy minerals from sands and sandstones of the Izu-Bonin Arc, Leg 126. In: Proceedings of the Ocean Drilling Program, Scientific Results, vol. 126, pp. 155–169.

Gandolfi, G., Paganelli, L., 1975. Il litorale toscano fra Livorno e il promontorio di Piombino (area campione Alto Tirreno): composizione, provenienza e dispersione delle sabbie. Bollettino della Societa Geologica Italiana 94, 1833–1854.

Gandolfi, G., Paganelli, L., 1984. Petrografia delle sabbie del litorale Tirrenico fra i Monti dell' Uccellina e Monte di Procida. Mineralogica et Petrographica Acta 28, 173–191.

Gansser, A., 1980. The Peri-Indian suture zone. In: Auboin, J., Debelmas, J., Latreille, M. (Eds.), Géologie des Châines Alpines Issues de la Téthys, Mémoires du Bureau de Recherches Géologiques et Minières 115, 140–148.

Garzanti, E., Andò, S., 2007. Heavy mineral concentration in modern sands: implications for provenance interpretation. In: Mange, M.A., Wright, D.T. (Eds.), Heavy Minerals in Use. Developments in Sedimentology (this volume).

Garzanti, E., Andò, S., Scutellà, M., 2000. Actualistic ophiolite provenance: the Cyprus Case. Journal of Geology 108, 199–218.

Garzanti, E., Andò, S., Vezzoli, G., Dell'Era, D., 2003. From rifted margins to foreland basins: investigating provenance and sediment dispersal across desert Arabia (Oman, UAE). Journal of Sedimentary Research 73, 572–588.

Garzanti, E., Andò, S., Vezzoli, G., Ali Abdel Megid, A., El Kammar, A., 2006. Petrology of Nile River sands (Ethiopia and Sudan): sediment budgets and erosion patterns. Earth and Planetary Science Letters 252, 327–341.

Garzanti, E., Canclini, S., Moretti Foggia, F., Petrella, N., 2002a. Unraveling magmatic and orogenic provenances in modern sands: the back-arc side of the Apennine thrust-belt (Italy). Journal of Sedimentary Research 72, 2–17.

Garzanti, E., Scutella', M., Vidimari, C., 1998. Provenance from ophiolites and oceanic allochthons: modern beach and river sands from Liguria and the Northern Apennines (Italy). Ofioliti 23, 65–82.

Garzanti, E., Vezzoli, G., Andò, S., 2002b. Modern sand from obducted ophiolite belts (Oman, U.A.E.). Journal of Geology 110, 371–391.

Garzanti, E., Vezzoli, G., Andò, S., Castiglioni, G., 2001. Petrology of rifted-margin sand (Red Sea and Gulf of Aden, Yemen). Journal of Geology 109, 277–297.

Garzanti, E., Vezzoli, G., Lombardo, B., Andò, S., Mauri, E., Monguzzi, S., Russo, M., 2004a. Collision-orogen provenance (Western and Central Alps): detrital signatures and unroofing Trends. Journal of Geology 112, 145–164.

Garzanti, E., Vezzoli, G., Andò, S., France-Lanord, C., Singh, S.K., Foster, G., 2004b. Sediment composition and focused erosion in collision orogens: the Brahmaputra case. Earth and Planetary Science Letters 220, 157–174.

Garzanti, E., Vezzoli, G., Andò, S., Paparella, P., Clift, P.D., 2005. Petrology of Indus River sands: a key to interpret erosion history of the Western Himalayan Syntaxis. Earth and Planetary Science Letters 229, 287–302.

Gazzi, P., 1965. On the heavy mineral zones in the geosyncline series, recent studies in the Northern Apennines, Italy. Journal of Sedimentary Petrology 35, 109–115.

Gazzi, P., Zuffa, G.G., Gandolfi, G., Paganelli, L., 1973. Provenienza e dispersione litoranea delle sabbie delle spiagge adriatiche fra le foci dell' Isonzo e del Foglia: inquadramento regionale. Memorie della Società Geologica Italiana 12, 1–37.

Gebauer, D., 1999. Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. Schweizerische Mineralogische und Petrographische Mitteilungen 79, 191–208.

Gill, J., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag, Berlin, 390pp.

Gioncada, A., Mazzuoli, R., Bisson, M., Pareschi, M.T., 2003. Petrology of volcanic products younger than 42 ka on the Lipari-Vulcano complex (Aeolian Islands, Italy): an example of volcanism controlled by tectonics. Journal of Volcanology and Geothermal Research 122, 191–220.

Glennie, K.W., Boeuf, M.G.A., Hughes-Clarke, M.W., Moody-Stuart, M., Pilaar, W.F.H., Reinhardt, B.M., 1974. Geology of the Oman Mountains. The Hague, Verhandelingen van het Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap Transactions, vol. 31, 423pp.

Hodges, K.V., 2000. Tectonics of the Himalaya and southern Tibet from two perspectives. Geological Society of America Bulletin 112, 324–350.

Hubert, J.F., 1962. A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy minerals assemblages with the gross composition and texture of sandstones. Journal of Sedimentary Petrology 32, 440–450.

Imbrie, J., Van Andel, T.H., 1964. Vector analysis of heavy mineral data. Geological Society of America Bulletin 75, 1131–1156.

Ingersoll, R.V., 1990. Actualistic sandstone petrofacies: discriminating modern and ancient source rocks. Geology 18, 733–736.

Ingersoll, R.V., Busby, C.J., 1994. Tectonics of sedimentary basins. In: Busby, C.J., Ingersoll, R.V. (Eds.), Tectonics of Sedimentary Basins. Blackwell, Oxford, pp. 1–51.

Johnsson, M.J., 1993. The system controlling the composition of clastic sediments. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments. Geological Society of America Special Paper 284, 1–19.

Klovan, J.E., Imbrie, J., 1971. An algorithm and FORTRAN-IV program for large scale Q-mode factor analysis and calculation of factor scores. Mathematical Geology 3, 61–77.

Knebel, H.J., Creager, J., 1974. Heavy minerals of the east-central Bering Sea continental shelf. Journal of Sedimentary Petrology 44, 553–561.

Korsch, R.J., Roser, B.P., Kamprad, J.L., 1993. Geochemical, petrographic and grain-size variations within single turbidite beds. Sedimentary Geology 83, 15–35.

Lachize, M., Lorand, J.P., Juteau, T., 1996. Calc-alkaline differentiation trend in the plutonic sequence of the Wadi Haymiliyah section, Haylayn massif, Semail ophiolite, Oman. Lithos 38, 207–232.

Le Fort, P., 1996. Evolution of the Himalaya. In: Yin, A., Harrison, M.T. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 95–109.

Mack, G.H., 1984. Exceptions to the relationship between plate tectonics and sandstone composition. Journal of Sedimentary Petrology 54, 212–220.

Mange, M.A., Maurer, H.F.W., 1992. Heavy Minerals in Colour. Chapman and Hall, London, 147pp.

Mange-Rajetzky, M., Oberhänsli, R., 1982. Detrital lawsonite and blue sodic amphibole in the Molasse of Savoy, France and their significance in assessing Alpine evolution. Schweizerische Mineralogische und Petrographische Mitteilungen 62, 415–436.

Marsaglia, K.M., Ingersoll, R.V., 1992. Compositional trends in arc-related, deep-marine sand and sandstone: a reassessment of magmatic-arc provenance. Geological Society of America Bulletin 104, 1637–1649.

Maynard, J.B., Valloni, R., Yu, H.-S., 1982. Composition of modern deep-sea sands from arc-related basins. In: Leggett, J.K. (Ed.), Trench-Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins, vol. 10. Geological Society of London Special Publication, pp. 107–119.

McBride, E.F., 1985. Diagenetic processes that affect provenance determinations in sandstones. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Reidel, Dordrecht, NATO ASI Series 148, pp. 95–113.

Mezzadri, G., Saccani, E., 1989. Heavy mineral distribution in Late Quaternary sediments of the Southern Aegean Sea: implications for provenance and sediment dispersal in sedimentary basins at active margins. Journal of Sedimentary Petrology 59, 412–422.

Michard, A., Boudier, F., Goffé, B., 1991. Obduction versus subduction and collision in the Oman case and other Tethyan settings. In: Peters, T., Nicolas, A., Coleman, R.G. (Eds.), Ophiolite Genesis and Evolution of Oceanic Lithosphere. Kluwer, Dordrecht, pp. 447–467.

Miyashiro, A., 1972. Metamorphism and Metamorphic Belts. Wiley, New York, NY, 492pp.

Morton, A., Hallsworth, C.R., 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. Sedimentary Geology 90, 241–256.

Morton, A.C., Hallsworth, C.R., 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. Sedimentary Geology 124, 3–29.

Murdmaa, I., Kazakova, V., Shirshov, P.P., 1980. Coarse-silt-fraction mineralogy of Japan Trench sediments, Deep Sea Drilling Project Legs 56 and 57. Initial Report of the Deep Sea Drilling Project, 56–57, 1005–1009.

Nechaev, V.P., 1991. Evolution of the Philippine and Japan Seas from the clastic sediment record. Marine Geology 97, 167–190.

Nechaev, V.P., Isphording, W.C., 1993. Heavy mineral assemblages of continental margins as indicators of plate-tectonic environments. Journal of Sedimentary Petrology 63, 1110–1117.

Noda, A., 2005. Texture and petrology of modern river, beach and shelf sands in a volcanic back-arc setting, northeastern Japan. The Island Arc 14, 687–707.

Parfenoff, A., Pomerol, C., Tourenq, J., 1970. Les minéraux en grains—méthodes d' étude et détermination. Masson, Paris, 578pp.

Peccerillo, A., 1985. Roman comagmatic province (central Italy): evidence for subduction-related magma genesis. Geology 13, 103–106.

Peters, C.S., Hollister, C.D., 1976. Heavy mineral characteristics and dispersal patterns from DSDP Leg 35, Southeast Pacific Basin. Initial Report of the Deep Sea Drilling Project 35, 291–300.

Pfiffner, O.A., Lehner, P., Heitzmann, P., Müller, S., Steck, A., 1997. Deep structure of the Swiss Alps. Results of NRP 20. Birkhäuser Verlag, Basel. 460pp.

Potter, P.E., 1978. Petrology and chemistry of modern big river sands. Journal of Geology 86, 423–449.

Potter, P.E., 1994. Modern sands of South America: composition, provenance and global significance. Geologische Rundschau 83, 212–232.

Prasad, S., Hesse, R., 1982. Provenance of detrital sediments from the Middle America trench transect off Guatemala, Deep Sea Drilling Project Leg 67. Initial Report of the Deep Sea Drilling Project, 67, 507–514.

Rihm, R., Henke, C.H., 1998. Geophysical studies on early tectonic controls on Red Sea rifting, opening and segmentation. In: Purser, B.H., Bosence, D.W.J. (Eds.), Sedimentation and Tectonics in Rift Basins: Red Sea-Gulf of Aden. Chapman and Hall, London, pp. 29–49.

Rolland, Y., Mahéo, G., Guillot, S., Pêcher, A., 2001. Tectono-metamorphic evolution of the Karakorum metamorphic complex (Dassu-Askole area, NE Pakistan): exhumation of mid-crustal HT-MP gneisses in a convergent context. Journal of Metamorphic Geology 19, 717–737.

Roser, B.P., Korsch, R.J., 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. Journal of Geology 94, 635–650.

Ross, D.A., 1971. Sediments of the northern Middle America Trench. Geological Society of America Bulletin 82, 303–322.

Sato, Y., 1981. Heavy mineral composition of Tertiary sediments at Deep Sea Drilling Project Sites 445 and 446, Northeastern Philippine Sea, Deep Sea Drilling Project. Initial Report of the Deep Sea Drilling Project, 58, 661–667.

Scheidegger, K.F., Kulm, L.D., Piper, D.J.W., 1973. Heavy mineralogy of unconsolidated sands in northeastern Pacific sediments, Leg 18, Deep Sea Drilling Project. Initial Report of the Deep Sea Drilling Project, 18, 877–887.

Schwab, F.L., 1975. Framework mineralogy and chemical composition of continental margin-type sandstone. Geology 3, 487–490.

Searle, M.P., Cox, J., 1999. Tectonic setting, origin, and obduction of the Oman ophiolite. Geological Society of America Bulletin 111, 104–122.

Serri, G., Innocenti, F., Manetti, P., 1993. Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of Neogene-Quaternary magmatism of central Italy. Tectonophysics 223, 117–147.

Slatt, R.M., Piper, D.J.W., 1974. Sand-silt petrology and sediment dispersal in the Gulf of Alaska. Journal of Sedimentary Petrology 44, 1061–1071.

Stattegger, K., 1987. Heavy minerals and provenance of sands: modeling of lithological end members from river sands of Northern Austria and from sandstones of the Austroalpine Gosau Formation (Late Cretaceous). Journal of Sedimentary Petrology 57, 301–310.

Stewart, R.J., 1976. Turbidites of the Aleutian abyssal plain: mineralogy, provenance, and constraints for Cenozoic motion of the Pacific plate. Geological Society of America Bulletin 87, 793–808.

Thamó-Bozsó, E., Kovács, L. Ó., 2007. Evolution of Quaternary to modern fluvial network in the Mid-Hungarian Plain, indicated by heavy mineral distributions and statistical analysis of heavy mineral data. In: Mange, M.A., Wright, D.T. (Eds.), Heavy Minerals in Use. Developments in Sedimentology (this volume).

Thornburg, T.M., Kulm, L.D., 1987. Sedimentation in the Chile Trench: petrofacies and provenance. Journal of Sedimentary Petrology 57, 55–74.

Ukstins, I.A., Renne, P.R., Wolfenden, E., Baker, J., Ayalew, D., Menzies, M., 2002. Matching conjugate volcanic rifted margins: ^{40}Ar/^{39}Ar chrono-stratigraphy of pre- and syn-rift bimodal flood volcanism in Ethiopia and Yemen. Earth and Planetary Science Letters 198, 289–306.

Weltje, G.J., 2002. Quantitative analysis of detrital modes: statistically rigorous confidence methods in ternary diagrams and their use in sedimentary petrology. Earth Science Reviews 57, 211–253.

Wenner, D.B., Taylor, H.P., 1974. D/H and O^{18}/O^{16} studies of serpentinization of ultramafic rocks. Geochimica et Cosmochimica Acta 38, 1255–1286.

Winkler, H.G.F., 1976. Petrogenesis of Metamorphic Rocks. Springer-Verlag, Berlin, 334pp.

Zuffa, G.G., 1987. Unravelling hinterland and offshore palaeogeography from deep-water arenites. In: Leggett, J.K., Zuffa, G.G. (Eds.), Marine Clastic Sedimentology—Concept and Case Studies. Graham and Trotman, London, pp. 39–61.

Zuffa, G.G., Normark, W.R., Serra, F., Brunner, C.A., 2000. Turbidite megabeds in an oceanic rift valley recording Jökulhlaups of Late Pleistocene glacial lakes of the Western United States. Journal of Geology 108, 253–274.