A CLASSIFICATION OF METAMORPHIC GRAINS IN SANDS BASED ON THEIR COMPOSITION AND GRADE

EDUARDO GARZANTI AND GIOVANNI VEZZOLI

Laboratorio di Petrografia del Sedimentario, Dipartimento di Scienze Geologiche e Geotecnologie, Università Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy

e-mail: eduardo.garzanti@unimib.it

ABSTRACT: **An operational classification of metamorphic grains in sands and sandstones is proposed with the aim of enhancing data reproducibility among operators and the potential of high-resolution bulk petrography in provenance studies. For each of four protolith compositions (metapelite, metapsammite/metafelsite, metacarbonate, metabasite), six archetype grains displaying increasing degree of recrystallization and foliation development are illustrated. Such a classification grid is specifically devised as a subsidiary tool for point counting with the Gazzi–Dickinson method. Traditional QFR parameters can also be easily recalculated from the data set obtained, thus meeting all possible needs (Decker and Helmold 1985; Suttner and Basu 1985). An experiment shows that usage of visual-comparison standards effectively minimizes operator variation and allows retrieval of crucial information during point counting in a reproducible way. A petrogenetic grid is presented as a subsidiary tool for classifying grains that include index minerals and to help correlation with dense-mineral data. The ''metamorphic index'' (MI) is introduced as an estimator of average metamorphic grade of source rocks. Our classification, an extension of concepts used first in the study of arc–continent collision in Taiwan (Dorsey 1988) and successfully expanded to interpret the evolution of continent–continent collision in the Himalayas (Najman and Garzanti 2000; White et al. 2002), proves to be fruitful in provenance analysis of foreland-basin sediments shed from Alpine-type, thick-skinned collision orogens, particularly when integrated with dense-mineral, geochemical, and geochronological data.**

INTRODUCTION

Quantitative clastic petrography is a powerful tool for interpreting provenance of modern and ancient terrigenous wedges, and it provides fundamental insights for reconstructing the tectonic evolution of mountain belts and associated sedimentary basins (Dickinson 1988). If chemical weathering and diagenetic modifications are limited, detrital modes faithfully mirror the geology of source terranes, and detailed information about lost eroded portions of orogens can be retrieved from the sedimentary archive (e.g., Johnsson 1993; Le Pera et al. 2001). Most crucial information is contained in rock fragments, which partially reproduce fabric and paragenesis of parent rocks. The resolution power of clastic petrography depends not only on the amount of significant details recorded during point counting but also on reproducibility of the results obtained (Griffiths and Rosenfeld 1954). In order to achieve both such aims, an effective classification scheme is needed for key framework grains.

The operational classification proposed by Dickinson (1970), which focuses on volcanic lithic types and is particularly useful in the study of volcanic arenites, does not take into account the great variety of metamorphic grains shed in abundance by collision orogens, which represent the volumetrically most significant source of sediment on Earth (Milliman and Meade 1983). Detritus from the metamorphic cores of orogenic belts can be transported via fluvial and turbiditic conveyor systems to virtually any type of basin, even thousands of kilometers away (Ingersoll et al. 1994). An accurate provenance diagnosis in these settings requires that we fully consider all relevant information about the metamorphic evolution and structural level of parent rocks, as revealed by texture and mineralogy of detrital grains. The aim of this article is to put forward a classification of metamorphic grains which allows us to retrieve important information during point counting of sand or sandstone samples, and ensures data reproducibility.

CLASSIFICATION OF METAMORPHIC GRAINS

Metamorphic grains are subdivided into four main groups (metapelite, metapsammite/metafelsite, metacarbonate, metabasite) according to protolith composition. The metapsammite/metafelsite category includes all quartz-rich grains, including metachert. For each group, five metamorphic ranks are identified according to increasing degree of recrystallization and progressive formation of cleavage and schistosity. Dimensions of newly grown micas is particularly useful in metapelite, metapsammite, and impure metacarbonate grains; index minerals are most commonly observed in metabasite grains.

The classification is proposed as a set of four visual tables, one for each group of metamorphic grains (Figures 1–4). Each table includes six grains demonstrating stages of increasing metamorphic recrystallization, from none (nonrecrystallized protolith) to complete (coarse newly grown crystals). Each figure thus depicts the ideal evolution of a source rock with given composition from the cold surface to the hot roots of the orogen. The twenty-four detrital grains illustrated as archetypes are from modern river sands from all over the Alpine–Himalayan belt. The illustration of these standards ensures clarity of definition, facilitates operational decisions during point counting, and favors reproducibility of data collected by different operators. Correlations between the five identified ranks and increasing metamorphic grade, from very low (prehnite–pumpellyite facies) to medium–high (amphibolite facies), have proved to be statistically valid for a wide data set including first-cycle modern sediments from the Alps to the Himalaya (Garzanti et al. 2003a; Garzanti et al. 2003b).

Rank 1 grains display development of weak slaty cleavage, incipient migration of quartz-crystal boundaries, or widespread calcite recrystallization (Völl 1976; Powell 1979). Clay is transformed into illite and chlorite, with growth of chlorite pods and sericite beards (''quartzite-like structures'' of Kossovskaya and Shutov, in Frey 1987). Original sedimentary or igneous textures are commonly recognizable (e.g., metasiltstone, metabasalt), as typically occurs in oceanic metamorphism. Rank 2 grains display strong fabric realignment, with pronounced migration of quartz-crystal boundaries and growth of sericite lamellae (''spine-like structures''; Frey 1987). Chlorite or Fe-rich epidote (pistacite) are widespread in metabasite grains. Rank 3 grains display development of schistosity, with growth of tiny micaceous lamellae and strain-free quartz or calcite crystals (Young 1976). Fe-poor epidote (clinozoisite) is common in metabasite grains. Size of newly grown minerals increases in rank 4 grains, including well-developed muscovite flakes or amphiboles (e.g., actinolite, glaucophane), to rank 5 grains, displaying a coarse mosaic of polyhedral crystals including biotite or hornblende (Vernon 1976).

The limit between ranks 4 and 5 is conventionally set at a groundmass crystal size of 62.5 μm (silt/sand boundary), the same adopted by workers using the Gazzi–Dickinson point-counting method (Dickinson 1970; Ingersoll et al. 1984; Zuffa 1985). As a result, fine-grained groundmass in lithic fragments of rank ≤ 4 is included in the lithic (L) pole, whereas coarse-grained rock fragments of rank 5 are assigned according to the single mineral under the crosshair (quartz, feldspar, accessory). The 62.5 μm

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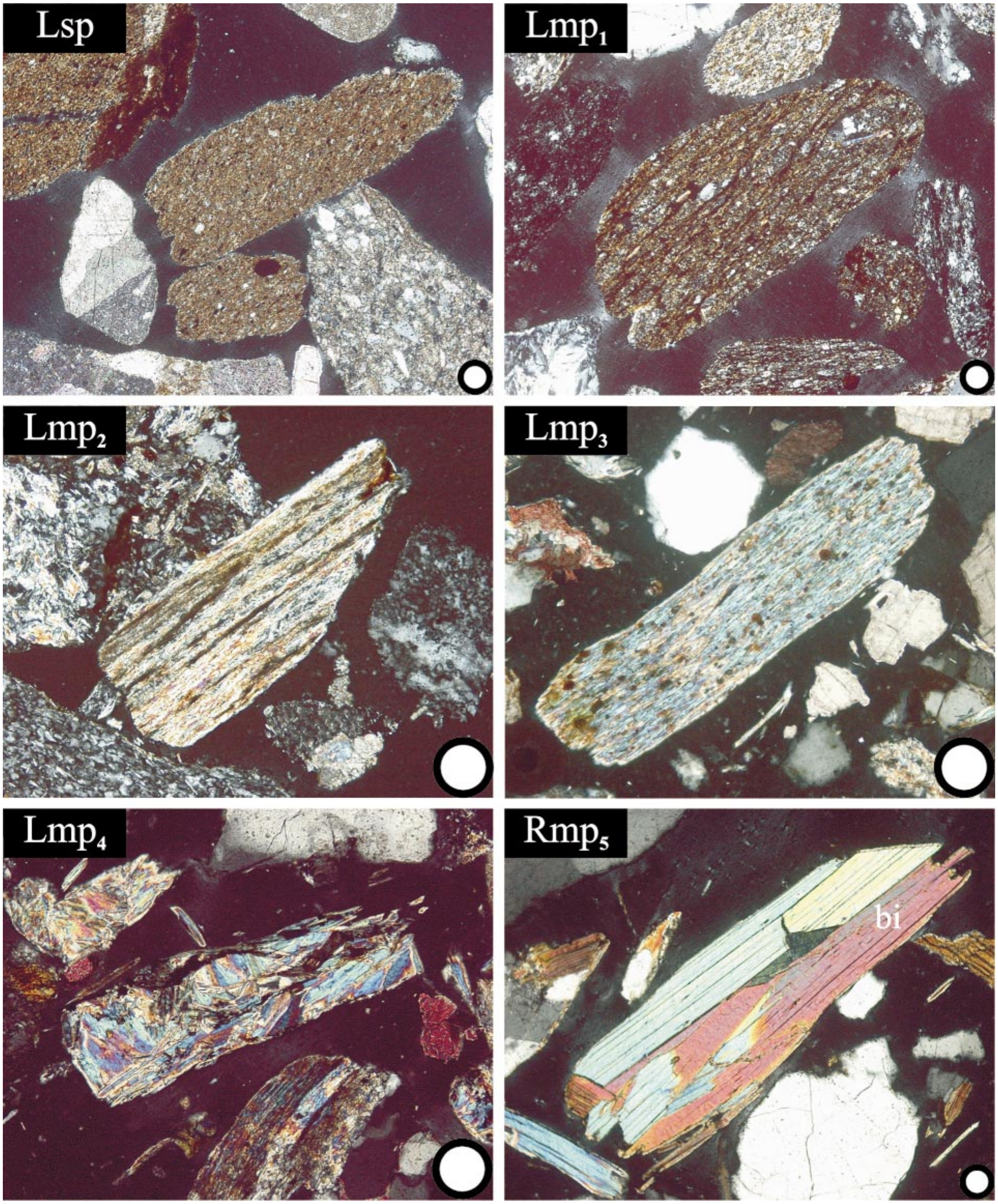

FIG. 1.—Metapelite grains. **Lsp)** Pelite lithic fragment (western Ligurian Alps). **Lmp$_1$)** Slate lithic fragment with rough cleavage (western Northern Caucasus). **Lmp$_2$)** Phyllite lithic fragment with strong cleavage (Ligurian Alps). **Lmp$_3$)** Micaceous schist lithic fragment (Engadine Window, Eastern Alps). **Lmp$_4$)** Muscovite schist lithic fragment (Western Alps). **Rmp$_5$)** Muscovite/biotite (bi) schist rock fragment (Central Alps). All white dots are 62.5 μm in diameter. All photos with crossed polars.

crystal-size limit thus marks a shift of detrital modes from lithic to quartzofeldspathic, which for instance in river sands from the Central Alps corresponds roughly with the boundary of the high-grade Lepontine dome (Garzanti et al. 2003a).

Our classification grid is an extension of concepts introduced to improve resolution of the petrographic method in the study of arc–continent collision in Taiwan (Dorsey 1988) and later expanded in reconstructing progressive stages of thrust-belt growth during continent–continent collision in the Himalayas (Table 1; Najman and Garzanti 2000; White et al. 2002). Dorsey (1988, her fig. 4) first distinguished lower-rank lithic fragments with

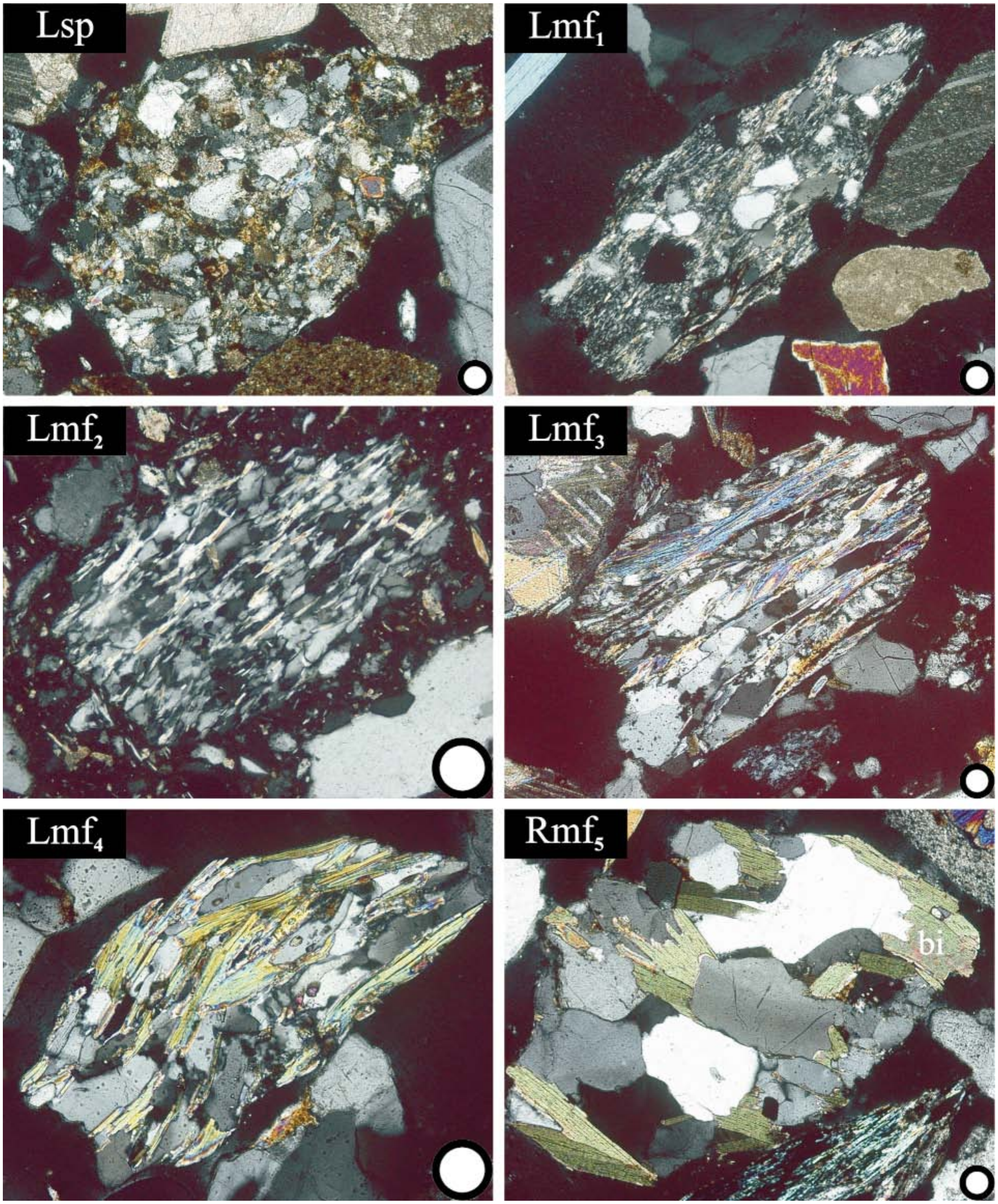

FIG. 2.—Metapsammite/metafelsite grains. **Lsp)** Sandy siltstone lithic fragment with detrital micas (western Ligurian Alps). **Lmf_1)** Metasiltstone lithic fragment with rough cleavage (Tethys Himalaya). **Lmf_2)** Quartz-sericite lithic fragment with strong cleavage (Lesser Himalaya). **Lmf_3)** Quartz-mica lithic fragment with schistosity (Tauern Window, Eastern Alps). **Lmf_4)** Muscovite gneiss lithic fragment (central Northern Caucasus). **Rmf_5)** Biotite (bi) gneiss rock fragment (High Himalaya). All white dots are 62.5 μm in diameter. All photos with crossed polars.

weakly crystalline sericite (slate, slaty siltstone, quartzite; her Lm1), from higher-rank lithic fragments with strongly crystalline micas up to 50 μm in length (phyllite–schist, phyllitic quartzite, quartz–mica–albite aggregate; her Lm2). White et al. (2002, their fig. 7) distinguished further between slate lithic fragments with sericite beards and weak rough cleavage (their Lm1), phyllite lithic fragments with sericite lamellae and strong cleavage (their Lm2), and schistose lithic fragments with muscovite (their Lm3). Such an approach proves to be particularly fruitful in provenance analysis

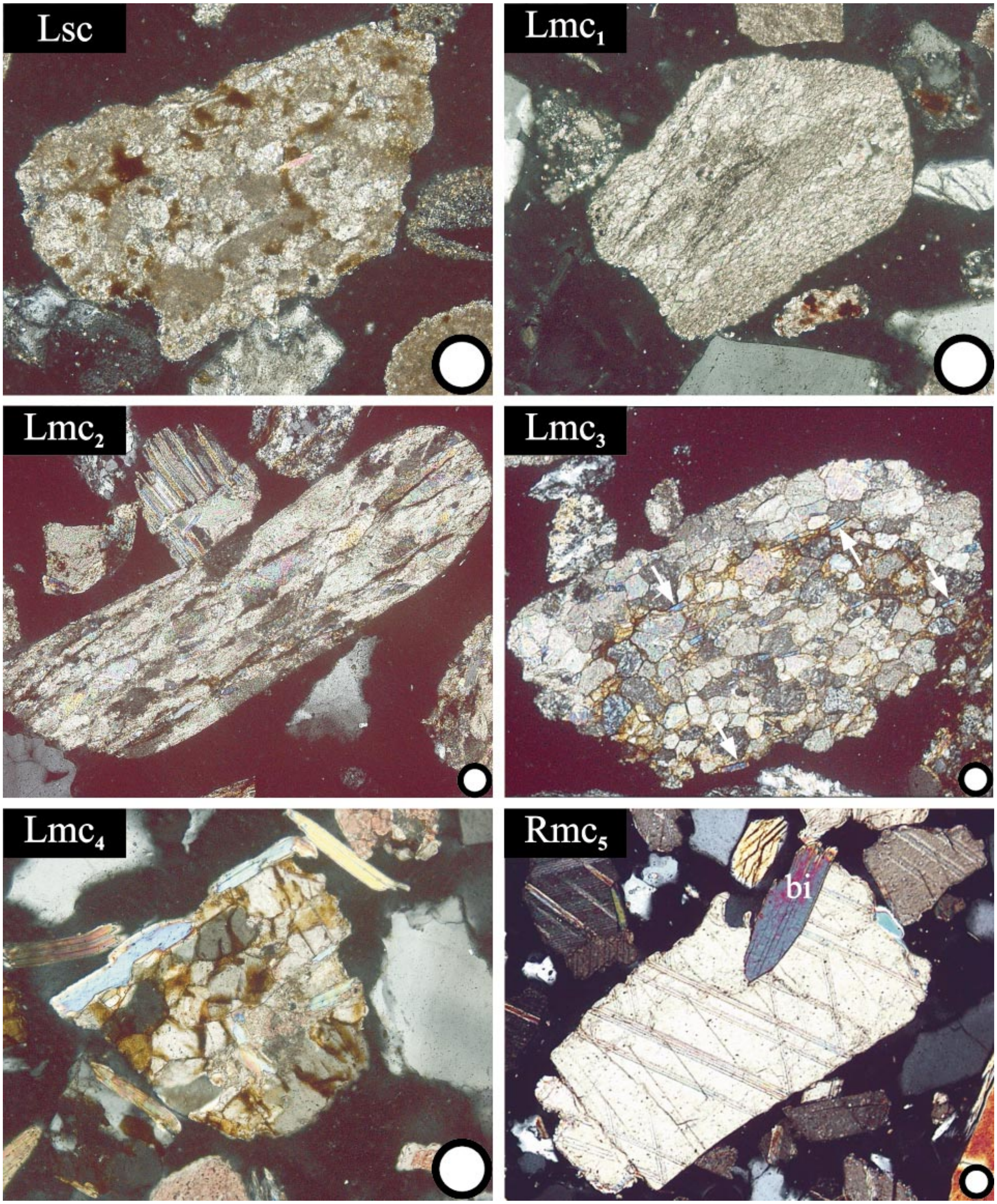

FIG. 3.—Metacarbonate grains. **Lsc)** Pelagic packstone lithic fragment with detrital micas (Northern Apennines). **Lmc_1)** Metalimestone lithic fragment with rough cleavage (Tethys Himalaya). **Lmc_2)** Metalimestone lithic fragment with strong cleavage (Northern Calcareous Alps). **Lmc_3)** Marble lithic fragment with tiny new micas (arrows; Apuane Window, Northern Apennines). **Lmc_4)** Muscovite calcschist lithic fragment (Central Alps). **Rmc_5)** Biotite (bi) calcschist rock fragment (High Himalaya). All white dots are 62.5 μm in diameter. All photos with crossed polars.

of foreland-basin clastic wedges derived from thick-skinned orogens, which consist mainly of metamorphic nappes stacked during attempted subduction of continental crust beneath oceanic, arc, or continental lithosphere (Doglioni et al. 1999; Searle and Cox 1999).

OPERATIONAL PROBLEMS

Any attempt at classification has its effective limits, particularly when, as in the present case, hybrid types exist between most categories. Meta-

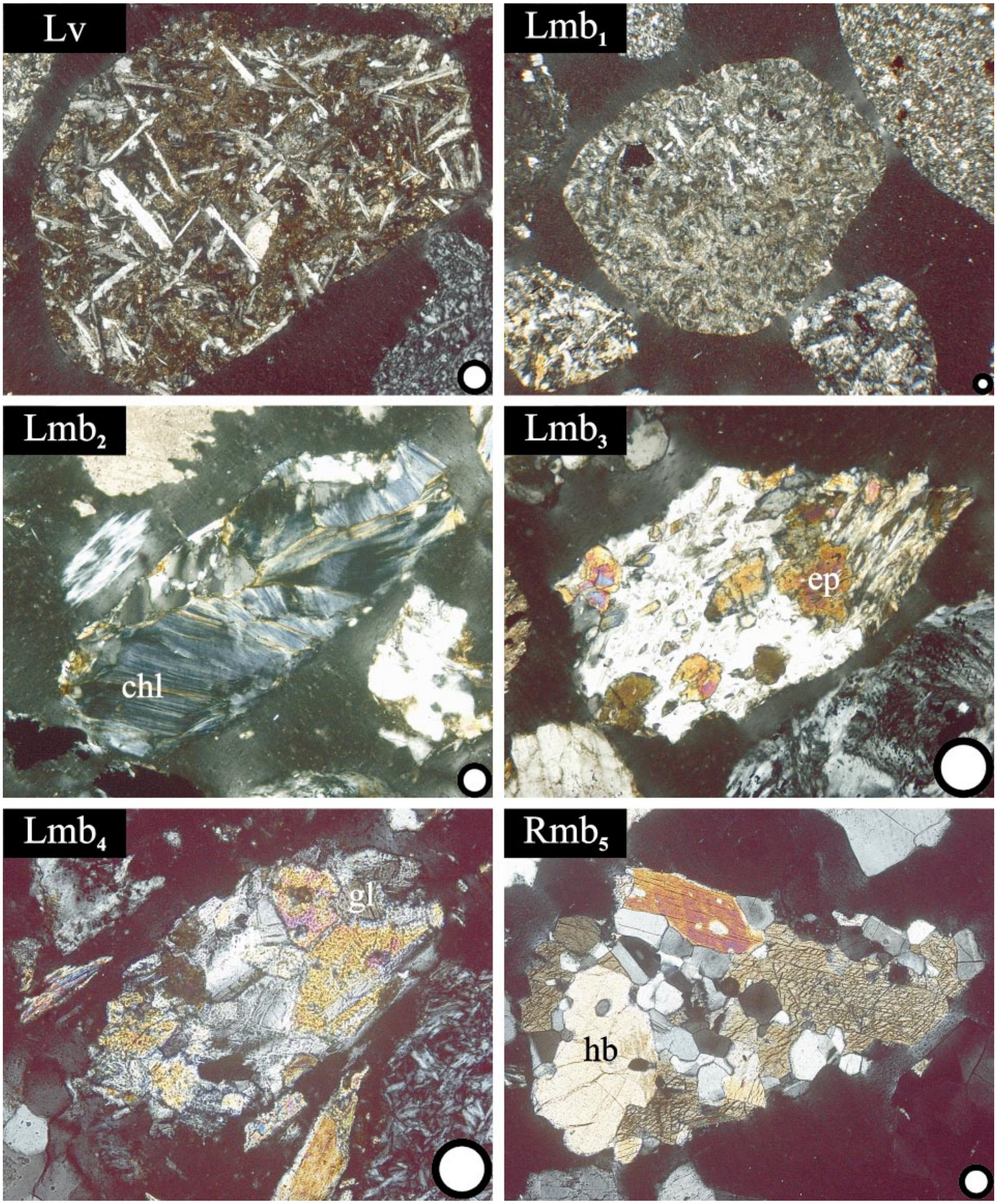

FIG. 4.—Metabasite grains. **Lv)** Basalt lithic fragment (Oman Ophiolite). **Lmb_1)** Metabasalt lithic fragment (Cyprus Ophiolite). **Lmb_2)** Chloritoschist lithic fragment (Ligurian Alps). **Lmb_3)** Prasinite lithic fragment (Ligurian Alps; ep = epidote). **Lmb_4)** Blueschist lithic fragment (Western Alps; gl = glaucophane). **Rmb_5)** Amphibolite rock fragment (Central Alps; hb = hornblende). All white dots are 62.5 μm in diameter. All photos with crossed polars.

sedimentary, metaigneous, and vein clasts may contain both felsic and mafic minerals (e.g., quartz–chlorite, quartz–epidote, quartz–hornblende), or metacarbonate grains may include abundant quartz. Such grains of intermediate composition are separated for various ranks during point counting, and next split equally between the appropriate compositional groups. Ultramafic grains (serpentinite, serpentineschist) are considered separately (Garzanti et al. 2002) and are not included in the present classification.

Grains of intermediate rank impose Solomonic decisions, which are particularly critical in the case of transition from diagenesis to metamorphism (shale versus slate; siltstone versus metasiltstone; basalt versus metabasalt).

TABLE 1.—*Attributes of metamorphic grains, their classification by previous workers, and their classification according to the scheme proposed herein.*

Metamorphic Rank	Texture	Phyllosilicates	Dorsey 1988	White et al. 2002	This Paper
None	unoriented	clay minerals	Ls, Lv	Ls, Lv	Ls, Lv
Very low	rough cleavage	illite, chlorite	Lm1	Lm1	Lm1
Low	strong cleavage	sericite		Lm2	Lm2
Medium	schistosity	tiny micas	Lm2	Lm3	Lm3
High	crystals $< 62.5\ \mu$m	muscovite			Lm4
Very high	crystals $> 62.5\ \mu$m	biotite	—	—	Rm5

According to the Gazz–Dickinson point-counting method, only aphanitic lithic fragments (crystal size $< 62.5\ \mu$m) are included in the lithic (L) pole; larger crystals ($>62.5\ \mu$m) in rock fragments (R) are tabulated in monomineralic categories.

This is particularly true for carbonate grains, where presence of argillaceous impurities is essential for confidently differentiating recrystallized sparite from metamorphic marble. Telltale features are most easily recognized in coarse-grained samples, whereas, in fine-grained sands, metacarbonate grains are represented largely by isolated spar crystals and rank 5 detritus mostly by single-mineral constituents. Most metamorphic source rocks are polymetamorphic or retrogressed to some extent, but the extreme complexity of metamorphic processes can hardly be unraveled for each single detrital grain. We thus consider the main signature only, and disregard weak overprints (e.g., chloritized biotite).

Finally, our scheme does not expressly consider varieties in metapsammite/metafelsite grains (e.g., presence or absence of feldspars) or explicitly

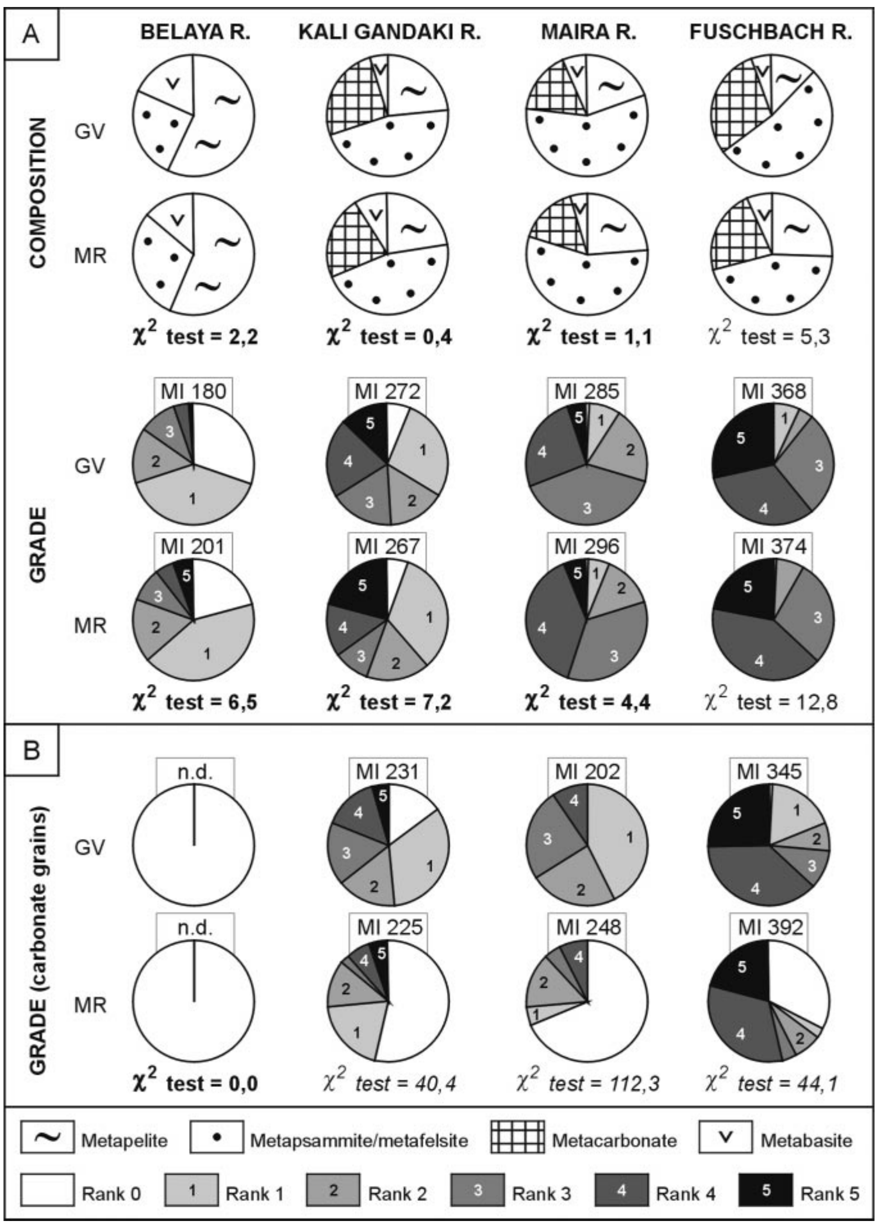

FIG. 5.—Operator variation in classifying metamorphic grains in modern sands from the Belaya, Kali Gandaki, Maira, and Fuschbach rivers. MI = Metamorphic Index; n.d. = not determined. **A)** Using visual comparison standards provided in Figures 1 to 4, grains were classified according to composition and grade with consistent results by operators GV (Giovanni Vezzoli) and MR (Michele Russo). **B)** Only classification of carbonate grains according to metamorphic grade revealed marked discrepancies between operators.

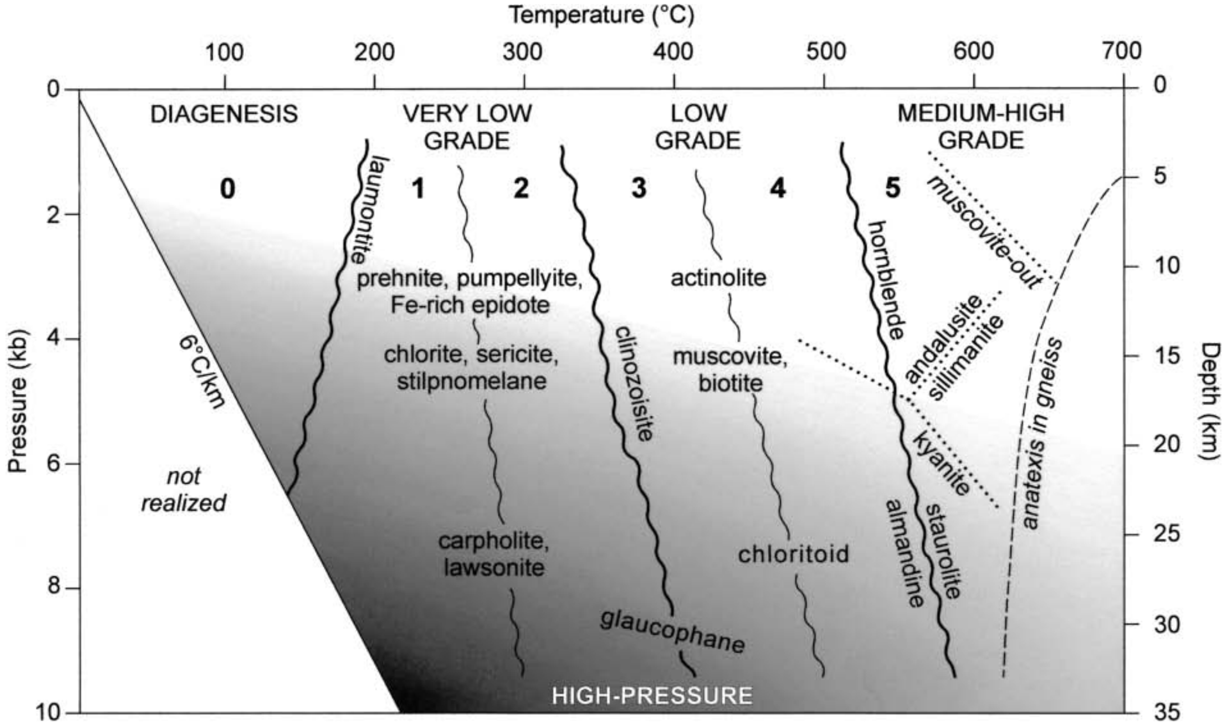

FIG. 6.—The proposed classification of metamorphic grains ties to the divisions of metamorphic grade as defined by Winkler (1976): rank 0 corresponds to the diagenesis field, ranks 1 and 2 to the very low-grade field, ranks 3 and 4 to the low-grade field, and rank 5 to the medium/high-grade field. The petrogenetic grid can thus be used not only as a subsidiary tool in classifying grains including index minerals (e.g., metabasite, high-rank metapelite) but also to compare detrital modes and dense-mineral suites in integrated provenance studies.

distinguish between sedimentary and igneous protoliths at low (metasandstone, quartzite, metachert versus metafelsite) to high rank (paragneiss versus orthogneiss). Also, it does not give specific emphasis to diagnostic grain types (e.g., hornfels, eclogite, granulite) and occurrence of index minerals (e.g., garnet, staurolite, kyanite, sillimanite), which convey important information on source rocks. In fact, if more than the two variables held as fundamental (i.e., composition and grade) are taken into account, the ensuing complications would render the classification cumbersome and, ultimately, ineffective. Nonetheless, any useful qualitative detail should be recorded during point counting, and considered in provenance diagnosis.

In an experiment designed to evaluate discrepancies in results obtained by two different operators (both graduate students with theses on Alpine-derived sediments), four samples of modern sand from rivers draining the Western Alps (Maira River), the Eastern Alps (Fuschbach River), the Northern Caucasus (Belaya River), and the Central Himalaya (Kali Gandaki River) were point counted, and metamorphic grains were classified according to composition and grade. Results are consistent in that the null hypothesis was not rejected by χ^2 test at the 20% significance level for the Belaya, Maira, and Kali Gandaki river sands, and at the 10% and 2% level for the Fuschbach River sand (Fig. 5A). Major discrepancies, however, were found in discriminating sparitic limestone grains from lower-rank, pure metacarbonate grains (Fig. 5B).

CORRELATION WITH DENSE-MINERAL AND GEOCHRONOLOGICAL DATA

The proposed classification allows direct comparison between petrographic and mineralogical data in integrated provenance studies. Recycled dense-mineral assemblages characterize sediments shed from sedimentary to very low-grade source rocks, because growth of new dense minerals during diagenesis to zeolite-facies metamorphism is insignificant. Rather, temperature increase during very low-grade metamorphism fosters dissolution, with resulting depleted assemblages progressively enriched in ultrastable minerals (zircon, tourmaline, rutile; Morton 1985). A few dense minerals grow at very low-grade conditions (Fe-rich epidote, prehnite, pumpellyite, stilpnomelane; carpholite and lawsonite at high pressure). At low grade (ranks 3 to 4), newly grown minerals are varied, more abundant, and coarser-grained (e.g., chinozoisite, chloritoid, actinolite; glaucophane in blueschist facies). At amphibolite facies (rank 5), hornblende from amphibolites and orthogneisses becomes dominant, associated with garnet, staurolite, kyanite, or sillimanite from metasedimentary rocks (Fig. 6).

Correlations with geochemical or geochronological data on single grains can also be predicted. At ranks 1 to 2, old inherited ages are expected from detrital minerals (e.g., von Eynatten and Gaupp 1999), with the exception of fission tracks on apatite and zircon. Young orogenic Ar/Ar ages are expected for newly grown micas at rank >3 (e.g., Najman et al 1997). At ranks 4 to 5 all mineral lattices and ages are progressively reset.

THE ''METAMORPHIC INDEX''

One primary aim in collision-orogen provenance is to assess metamorphic grade of source rocks. For this purpose, average rank of metamorphic grains for each analyzed sand or sandstone sample can be expressed by a ''metamorphic index'' (MI), a weighted sum where percentages of rank 1, rank 2, rank 3, rank 4, and rank 5 grains are multiplied by 1, 2, 3, 4, and 5, respectively. The MI index thus ranges from 100 (only rank 1 lithic fragments) to 500 (only rank 5 rock fragments). If major difficulties are encountered in distinguishing metamorphic rank of specific grain types (e.g., metacarbonate grains), these are better not considered in recalculating the MI index.

In order to test the reliability of the MI index, we used first-cycle metamorphiclastic detritus from the Western and Central Alps, an area where regional metamorphism has been studied in great detail. We compared features of metamorphic rock fragments carried by mountain rivers (63 samples; database in Garzanti et al. 2003a) with average peak temperatures

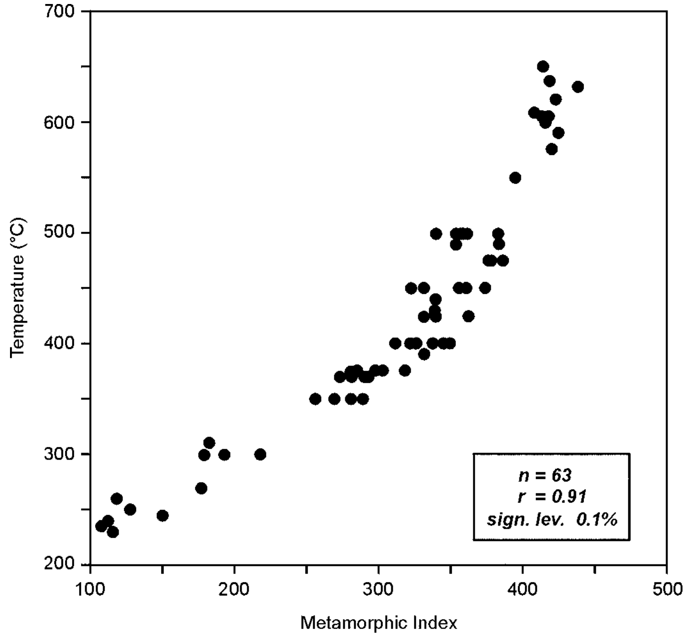

FIG. 7.—Excellent correlation between the ''metamorphic index'' (measured for 63 Alpine river sands; Garzanti et al. 2003a) and average peak metamorphic temperatures (determined for each river basin according to Frey et al. 1999).

reached during Tertiary metamorphism (as determined for each river basin according to the Metamorphic Map of the Alps; Frey et al. 1999). The MI index in Alpine river sands is seen to consistently increase from anchi-metamorphic (~ 250°C), ''carpholite-zone'' (~ 300°C), blueschist- to greenschist-facies (350–500°C), and amphibolite-facies source rocks (550–675°C), and thus proves to be an excellent estimator of peak temperatures (Fig. 7).

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