Mixed carbonate-siliciclastic sedimentation on a tectonically active margin: Example from the Pliocene of Baja California Sur, Mexico

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ABSTRACT

Bioclast-rich, coarse-grained deposits in the Pliocene Loreto basin provide a record of mixed carbonate and siliciclastic sedimentation at the steep hanging-wall margin of this small, fault-controlled basin. Sedimentary facies consist of sand- to gravel-sized carbonate debris mixed with volcaniclastic sand and gravel in a proximal to distal facies tract that includes matrix-rich and matrix-poor shelly conglomerate, impure calcirudite and calcarenite, mixed-composition turbidites, and bioturbated calcarenitic sandstone. Carbonate material was produced by mollusks and other benthic organisms on a narrow, high-energy shelf and mixed with volcaniclastic sand and gravel in cross-shelf channels. These mixtures were transported down a steep subaqueous slope by debris flows, grain flows, and turbidity currents, forming foresets and bottomsets of marine Gilbert-type deltas. This style of mixed carbonate-siliciclastic sedimentation has not been documented in detail elsewhere but should be locally abundant in the stratigraphic record of fault-bounded basins, particularly those with cool or nutrient-rich waters that support relatively few binding and framework-building faunas. Recognition of similar facies in other settings can provide useful insights into ancient conditions of carbonate production, oceanography, climate, and tectonics.

INTRODUCTION

Mixed carbonate-siliciclastic sedimentation is common in middle- to low-latitude shelf and platform settings and can be controlled by a variety of physical and biological processes (Choi and Ginsburg, 1982; Mount, 1984; Flood and Orme, 1988; Pilkey et al., 1988). Mixing can occur when terrigenous sand and mud are delivered to a carbonate shelf during storms, causing temporary termination or diminution of carbonate production (e.g., Kreisa, 1981). Storms may winnow and transport skeletal carbonate material from outer reef or bank settings into inner shelf and lagoonal areas of fair-weather siliciclastic sedimentation, producing stratified bioclastic deposits and interbedded mixtures (e.g., Kelling and Mullin, 1975). Rarely, clastic carbonate material is derived from older lithified carbonate terranes, in which case production of carbonate sediments is unrelated to basinal dynamics or paleoecology of the shelf (Mount, 1984).

In this paper we introduce a previously undocumented style of mixed carbonate and siliciclastic sedimentation by using an example from the tectonically active Pliocene Loreto basin in Baja California Sur, Mexico (Fig. 1). In this setting, molluscan carbonates were produced on a narrow, high-energy shelf rimmed by Miocene volcanic bedrock, mixed with volcaniclastic sand and gravel in cross-shelf channels, and transported down steep, unstable slopes into the flanking basin by a variety of subaqueous sediment-gravity flows. These flows produced a diverse array of mixed bioclastic and volcaniclastic deposits that are described and interpreted in the following. Although not previously documented, this style of mixed carbonate-siliciclastic sedimentation should be locally abundant in the stratigraphic record and can be useful for reconstructing paleogeography, oceanography, climate, and tectonics of ancient sedimentary basins.

BASIN SETTING AND STRATIGRAPHY

The Pliocene Loreto basin is a small, transtensional half-graben basin that formed during development of the modern transform-rift plate boundary in the Gulf of California (Fig. 1; Umhoefer et al., 1994; Umhoefer and Dorsey, 1997). The basin formed by westward tilting and asymmetric subsidence between ca. 5(?) and 2 Ma, and it contains a thick, diverse assemblage of sedimentary rocks that accumulated rapidly in nonmarine, deltaic, and marine environments (Dorsey et al., 1995; Dorsey and Umhoefer, 1999). The stratigraphy of the Loreto basin is divided into four sequences that record fault-controlled basin evolution: (1) relatively slow deposition in a nonmarine half graben; (2) very rapid westward tilting, subsidence, and deposition of footwall-derived marine Gilbert-type fan deltas and associated nonmarine and marine facies; (3) continued rapid subsidence and deposition of impure bioclastic carbonates derived from the eastern hanging-wall dip slope; and (4) abrupt foundering of the basin to outer shelf depths followed by filling with marine mudstone and limestone (Dorsey et al., 1995; Dorsey and Umhoefer, 1999). Sequence 3 (this study) contains abundant bioclastic carbonates and associated volcaniclastic sediments that accumulated in foresets and bottomsets of marine Gilbert-type deltas (Fig. 2) at the eastern margin of the Loreto basin. These coarse-grained deltas prograded to the west and northwest into the basin in response to fault-controlled uplift of the hanging-wall tilt block, which created a new source of siliciclastic sediment in the Sierra Microondas (Fig. 1) and a narrow shelf for carbonate production.

SEDIMENTOLOGY OF MIXED FACIES

Mixed carbonate-siliciclastic deposits in sequence 3 vary considerably in grain size, sorting, sedimentary structures, thickness, and relative

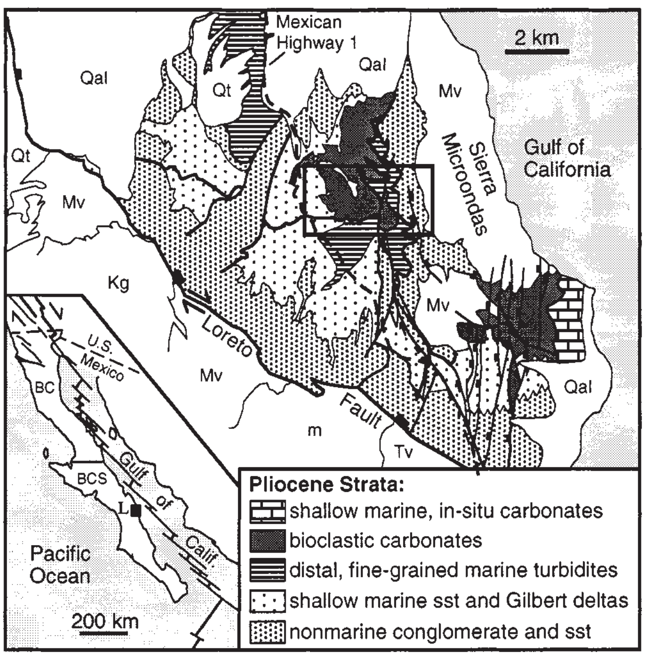

Figure 1. Geologic map of Loreto basin and regional tectonic setting (inset). Bioclastic carbonates include mixed carbonate and volcaniclastic deposits of this study (box shows location of this study). Abbreviations: BC—Baja California; BCS—Baja California Sur; Kg—Cretaceous granitoids; L—Loreto basin; m—pre-Cretaceous metamorphic rocks; Mv—Miocene volcanic rocks; Qt—Quaternary terrace deposits; Qal—Quaternary alluvium; Tv—Tertiary volcanic rocks; sst—sandstone.

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Figure 2. View looking north at large-scale foresets of Gilbert-type fan delta, showing transport toward west. Upper foresets (dark colored) are matrix-rich shelly conglomerate (facies 2); lower foresets (light-colored) are transported calcirudite and calcarenite (facies 4) and bipartite conglomerate and calcarenite (facies 3). Thickness of exposed foresets is ~50 m.

percent of carbonate and siliciclastic components (Table 1; Fig. 3). These deposits are exposed in a laterally contiguous facies tract that displays an overall decrease in grain size from proximal Gilbert-type delta foresets (Fig. 2) to medial and distal bottomsets. Carbonate grains consist mainly of transported calcitic skeletons, especially scallops, oysters, barnacles, and bryozoans, that range from sand-sized carbonate grains to shell fragments and unbroken shells. Siliciclastic grains consist of volcaniclastic sand and gravel, including andesitic to basaltic rock fragments and sand-sized minerals (typically plagioclase and pyroxene) derived from Miocene andesites and basaltic andesites to the east. Rock names used in this paper (Table 1) employ the carbonate or siliciclastic terms depending on which component is greater than 50% (e.g., sandy calcarenite vs. calcarenitic sandstone), but in reality, lithologies fall in a continuum of carbonate:siliciclastic mixtures ranging from 90:10 to 10:90. Mixtures between ~70:30 and 30:70 are most common. In this study, sand is used to designate sand-sized volcanic grains <2 mm in diameter, conglomerate refers to deposits of gravel-sized volcanic clasts, calcarenite indicates sand-sized carbonate grains, hash refers to carbonate grains 2–10 mm in diameter, and calcirudite indicates gravel-sized carbonate particles (Table 1).

Facies 1 is preserved locally as thin topset deposits and consists of thin- to medium-bedded clast-supported conglomerate, shelly sandstone, and shell beds (sandy calcirudite). Shell beds contain abundant articulated organisms in life positions, particularly scallops, oysters, barnacles, and gravel-nucleated bryoliths. These components are distributed in a mosaic of sand, gravel, and shell patches that record benthic colonization and tractional reworking by waves and currents in a shallow-marine shelf setting.

Matrix-rich shelly conglomerate (facies 2) is characterized by poor sorting, lack of current stratification, ungraded or inversely graded clast fabric, matrix-supported texture, and predominantly disarticulated and broken shells of robust species (Fig. 3A; Table 1). Shelly conglomerate records deposition by cohesive subaqueous debris flows in proximal Gilbert-type delta foresets, rarely continuing down to the base of foreset slopes, where they terminate abruptly.

Bipartite deposits (facies 3) consist of erosionally based, clast-supported conglomerate overlain by massive pebbly calcirudite and sandy calcarenite (Fig. 3, B and C; Table 1). Carbonate grains are well sorted and in extreme instances consist of closely stacked concave-up valves of a single scallop or barnacle species. Inverse and normal grading in basal gravel layers, abrupt but nonerosive contacts between gravel and calcirudite, and close association with subaqueous debris flows and turbidites suggest deposition from high-concentration grain flows and overflowing, lower density turbulent suspensions (e.g., Lowe, 1982; Nemec, 1990; Falk and Dorsey, 1998). Concentration of calcirudite and calcarenite in the upper parts of these deposits is attributed to hydraulic sorting and segregation of lighter carbonate shell debris from heavier volcaniclastic gravel.

Facies 4 consists of massive to relict-bedded calcirudite and calcarenite with relatively minor lithic sand, granules, and small pebbles (Fig. 3C). Calcirudite and calcarenite record deposition from bioclastic turbulent suspensions, or high-density turbidity currents, that bypassed the less mobile basal gravel flows of facies 3 and accumulated as amalgamated run-out deposits on lower foresets and bottomsets of prograding Gilbert-type deltas.

Facies 5 consists of mixed-composition turbidites characterized by rhythmic alternations of sharp-based sandy calcarenite, calcarenitic sandstone, and mudstone, with gradational contacts between units and abundant normal grading (Fig. 3D; Table 1). These are interpreted to record a further degree of run-out, dilution, hydraulic sorting, and deposition of bioclastic and volcaniclastic detritus by low-density turbidity currents in distal bottomsets.

Facies 6 consists of burrow-mottled, massive to weakly bedded fine-grained sandstone and calcarenitic sandstone that record slow deposition by distal low-density turbidity currents and strong biogenic reworking.

TABLE 1. SUMMARY OF MIXED CARBONATE-SILICICLASTIC FACIES, LORETO BASIN

Facies	Origin	Description	Interpretation
1. Cgl, sst, and mollusk beds	In situ	Clast-supported cgl, shelly lithic sst, and mollusk beds (esp. scallops & oysters). Abundant encrusting bryozoans, barnacles, and oysters on clasts	High-energy traction sedimentation in shallow shelf; mollusk banks forming on sand-gravel substrate
2. Matrix-rich shelly cgl	Transported	Poorly sorted, matrix-supported cgl (clasts up to small boulders), beds up to ~2 m thick. Contains abundant admixed shells and calcarenite in matrix (Fig. 3A.)	Subaqueous debris flows on Gilbert-type delta foresets; carbonate and lithic components fully mixed
3. Bipartite cgl and calcarenite	Transported	Clast-rich shelly lithic cgl overlain by ungraded calcirudite and calcarenite with admixed lithic sand to small pebbles (Fig. 3B)	Gravel-rich grain flow (traction carpet) formed at base of bioclastic turbidity currents; hydraulic sorting and deposition on Gilbert-type delta foresets
4. Massive calcirudite and calcarenite	Transported	Moderately sorted, massive to relict-bedded calcirudite and calcarenite with shell fragments and lithic sand to small pebbles (Fig. 3C)	Deposition from bioclastic turbidity currents on lower foresets and bottomsets; run-out from bipartite cgl and calcarenite
5. Mixed-composition turbidites	Transported	Rhythmic alternations of sharp-based lithic-sandy calcarenite, planar stratified calcarenitic lithic sst, and mudstone. Gradational contacts between units, abundant normal grading (Fig. 3D)	Fine-grained, low-density turbidity currents in bottomsets; carbonate and lithic components sorted by contrasting hydraulic properties
6. Bioturbated lithic sst	Transported	Burrow-mottled, massive to relict-bedded fine-grained lithic sst with minor calcarenite and hash	Distal run-out past mixed turbidites, bioturbation exceeds sedimentation rate

Note: "lithic" = volcaniclastic sand and gravel; cgl = lithic conglomerate; sst = lithic sandstone; calcarenite = bioclastic carbonate composed of sand-sized carbonate grains of ≤2 mm diameter (grainstone); hash = bioclastic carbonate rock composed of carbonate grains of 2-10 mm diameter (lower rudstone); and calcirudite = bioclastic carbonate composed of gravel-size carbonate grains >1 cm diameter (rudstone).

DEPOSITIONAL MODEL

Figure 4 depicts our interpretation of the depositional systems and resulting sedimentary facies that formed on the eastern margin of the Loreto basin during sequence 3 time. Uplift and westward tilting created a rapidly eroding eastern source area that delivered volcaniclastic gravel and sand to small coastal alluvial fans. Alluvial-fan facies are not directly observed because of postdepositional erosion, but their presence is inferred from abundant coarse volcaniclastic gravel in proximal foresets and rare topsets of marine Gilbert-type deltas. A narrow (<1 km) marine shelf formed along the western fringe of these fans and provided a shallow-water sand and gravel habitat for shelly macrobenthos. Shifting cross-shelf channels incorporated molluscan shells and shell fragments, and mixed bioclastic-volcaniclastic detritus was transported to the top of steep delta slopes, where oversteepening caused slope failures and sediment avalanching (e.g., Nemec, 1990). Westward transport and deposition of mixed bioclastic and volcaniclastic sediment were dominated by sediment-gravity flows that underwent progressive down-transport transformation from cohesive debris flows to bipartite flows and low-density turbidity currents (Fig. 4).

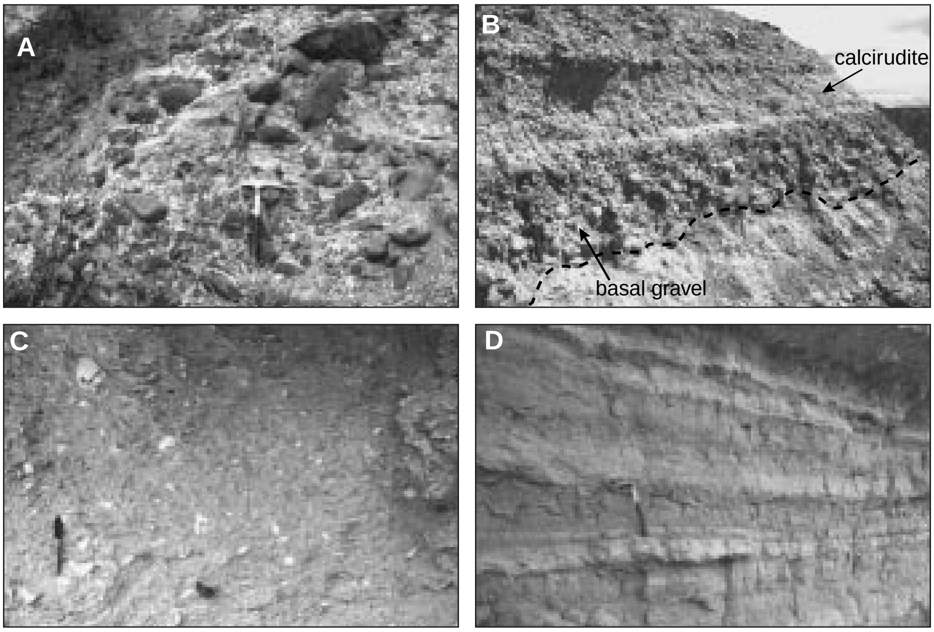

Figure 3. Mixed bioclastic and volcaniclastic deposits. A: Poorly sorted matrix-rich shelly conglomerate (facies 2). B: Bipartite conglomerate and calcirudite (facies 3). C: Massive calcirudite and calcarenite (facies 4). D: Mixed-composition turbidites (facies 5).

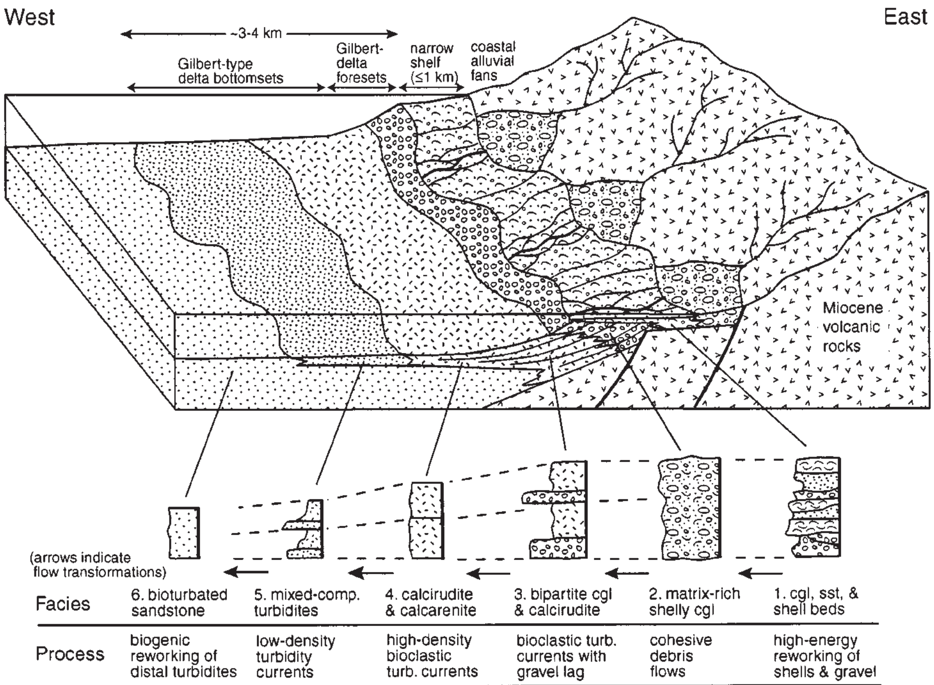

Figure 4. Conceptual model for transport and deposition of mixed bioclastic-volcaniclastic lithofacies at eastern margin of Pliocene Loreto basin. Mollusk-rich carbonates were produced in shoals and banks in narrow shelf setting, reworked into cross-shelf channels, and transported down steep basin-margin slope by subaqueous mass flows. Idealized lateral variation in lithofacies records downslope transformation from debris flows to high- and low-density turbidity currents. See text for discussion; abbreviations: comp.—composition, turb.—turbidity, cgl—conglomerate, sst—sandstone.

DISCUSSION

Mixed carbonate-siliciclastic sediments have been observed in other fan-delta systems where they typically consist of dominantly autochthonous thin shell beds and patch reefs that record periods of transgression or stalled progradation, as in the Eocene southern Pyrenees (Lopez-Blanco, 1993), Neogene Betic Cordillera (Dabrio, 1990), and Pliocene footwall-derived fan deltas of the western Loreto basin (Dorsey et al., 1995). In the Red Sea, Holocene deposits make up a complex mosaic of siliciclastic fans, fringing reefs, and biogenic (bioturbated) mixtures of longshore-transported carbonate and siliciclastic sand (Hayward, 1985). Voluminous physical mixing of lithologies by subaqueous debris flows and turbidity currents, as described here, has not been documented in detail elsewhere. The two closest analogs we are aware of are: (1) rare, thin mass-flow deposits containing >50% barnacle debris in Miocene sandy conglomeratic fans of the Tabernas basin, Spain (Doyle et al., 1996), and (2) traction transport of loose barnacle-bryozoan debris from thrust-cored antiforms and strike-slip blocks into adjacent structural troughs (Neogene of New Zealand; Kamp and Nelson, 1987).

A combination of conditions apparently was required to form the coarse-grained mixed facies described here for the Loreto basin. In particular, mobilization and rapid downslope transport of large volumes of loose carbonate particles require (1) a relatively high rate of carbonate production in shallow waters but without extensive algal and/or coral binding or early cementation; (2) relative to carbonate production, a slow rate of carbonate breakdown by processes such as dissolution, bioerosion, and maceration, so that carbonate grains could survive temporary storage in shallow waters; and (3) strong tectonic uplift to produce steep basin-margin gradients, slope failure, and downslope evolution of subaqueous sediment-gravity flows. Condition 1 appears to require nontropical temperatures and/or an elevated nutrient load, which would curtail binders, suppress inorganic cementation, and favor the dominance of mollusks and barnacles (James, 1997). Average accumulation rates for such heterozoan carbonates on Quaternary shelves are 1–100 cm/k.y., an order of magnitude lower than those for chlorozoan shallow-water reefs (1000 cm/k.y.); however, at the high end they match accumulation rates for tropical tidalites, oolites, and deeper water (>5 m) reefs (James, 1997), and thus are capable of feeding steep-sloped delta systems. These rates reflect the net outcome of total production and total postmortem destruction, suggesting that condition 2 also would have been met in the Loreto basin. The absence of micritized shells is consistent with cooler temperatures or elevated nutrients, because micritization is known to take place only in warm tropical chlorozoan sediments (Alexandersson, 1972).

In the Loreto basin (26°N) during Pliocene time, the conditions described herein were controlled by several regional-scale geologic and climatic factors. The Pliocene Gulf of California and adjacent embayments such as the Loreto basin were likely affected by oceanographic and physiographic conditions similar to those of the modern gulf: a long, narrow marine body deeper at its mouth than at the head, with a semiarid to arid climate. The modern gulf is a subtropical area of exceptionally high productivity resulting from its thermohaline circulation: warm surface water created in the northern gulf flows out at the southern end, cool nutrient-rich Pacific water is drawn into the gulf at depth, and seasonal shifts in large-scale wind patterns cause upwelling of these deep waters along both the Baja and Sonoran (mainland) coasts (Alvarez-Borrego and Lara-Lara, 1991; Bray and Robles, 1991). Upwelling conditions probably existed in the Loreto area during Pliocene time and can explain the taxonomic composition of the Loreto benthic fauna, which is typical of cool and/or nutrient-enriched waters (classic heterozoan association) rather than the warmer and clearer subtropical conditions that would be expected in the absence of upwelling. Reduced water clarity due to terrigenous input from nearby eroding uplands may have also contributed to conditions that favored mollusks and inhibited carbonate production by more typical subtropical corals and encrusting algae. The requisite narrow shelf setting, steep bathymetric gradient, and rapid input of coarse terrigenous sediment (condition 3) resulted from rapid tectonic uplift in the hanging-wall tilt block of a tectonically active, fault-bounded basin.

CONCLUSIONS

Mixed bioclastic and volcaniclastic facies in the Loreto basin were deposited by a variety of submarine debris flows and turbidity currents in Gilbert-type deltas that prograded away from the active eastern margin of the basin. This style of mixed carbonate and siliciclastic sedimentation requires a specific set of tectonic and oceanographic conditions: (1) high rate of carbonate production in shallow waters without extensive algal and/or coral binding or early cementation; (2) slow rate of carbonate breakdown relative to production rate so that the net supply of carbonate debris is comparable to that of coarse siliciclastic detritus; and (3) steep basin-margin gradients that are necessary for rapid downslope transport of sediment mass flows. These conditions existed in the tectonically active Pliocene Loreto basin, where high productivity of nontropical carbonates (mollusk-dominated faunas) resulted from strong upwelling of nutrient-rich cool waters in the Gulf of California. Similar facies are likely to be preserved in other basins, where they can be useful for better understanding past climatic, oceanic, and tectonic conditions of sedimentation.

ACKNOWLEDGMENTS

Supported by the donors of the Petroleum Research Fund (administered by the American Chemical Society) and by the National Science Foundation (grant EAR-9526506). We thank Paul Umhoefer for useful discussions and insights during the course of the study, and James Boles and an anonymous reviewer for helpful comments on the manuscript.

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Manuscript received February 8, 1999
Revised manuscript received July 6, 1999
Manuscript accepted July 16, 1999