IENT:

ɔm the Betics to the Oman
ges, to small clasts in flysch
amafics against the country
: and (or) exogeosynclinal
:ontact relationships of such
wildflysch, transported blue-
esent a variety of tectonic-
d and telescoped into juxta-
obduction problem that is
:lts, or from ophiolitic base-
al blocks, or by the develop-
that have a continent-facing
the final stages of obduction.
edded, deformed, and meta-
s. Such assemblages, whose
eanic realms by the collision
lerable distances from their
in steeply dipping mélange
sutures that did not involve

between origin and emplace-
ior, ophiolite generation and
suggesting the development
late boundary. Second, there
it portions of the pre-Alpine
eading along accreting plate
irope. The likeliest candidate
khide Depression, and south
n for most of the Mesozoic
ne of which (e.g., Pontide

consistent with the relative
plate accretion history. Most
faults and subduction zones
diabase complexes would lie
avorable circumstances (e.g.,
odel. However, in most ex-
mplacement prohibit such a

DAVID BLOOM

EUGEOSYNCLINAL BASEMENT AND A COLLAGE CONCEPT OF OROGENIC BELTS

JAMES HELWIG
Case Western Reserve University, Cleveland, Ohio

ABSTRACT

The perception that orogens may be divided into eugeosynclines having abundant volcanic rocks and miogeosynclines lacking volcanics triggered the hypothesis that eugeosynclines are perhaps ancient island arcs. Subsequent geophysical and geological studies supported a concept of eugeosynclines as at least partly comprising ancient oceanic terranes as well as arcs. It has become increasingly evident that to understand the role of orogenesis in crustal evolution the extent of oceanic crust in the basement of eugeosynclinal belts must be determined.

A consistent feature of eugeosynclines is their composite nature as manifest in elongate tectono-stratigraphic units or tectonic elements. The stratigraphic, tectonic, and plutonic and metamorphic evolution of each element is distinct and yet is partly related to adjacent elements. Major tectonic elements are separated by long-lived faults. The lithological sequence of each element is correlated with its basement type and the nature and history of its boundaries. Ancient eugeosynclinal tectonic elements may be elucidated by comparison with modern tectonic elements clearly related to plate motions. The basement of such tectonic elements is highly varied, and thus all eugeosynclinal zones are not ensimatic.

Tectonic processes play a key role in determining preservation and mode of occurrence of oceanic lithosphere in orogens. To survive orogenesis, oceanic crust must have a thick low-density cap or be tectonically intercalated with thick lower density materials. Preservation of oceanic crust and mantle within orogens therefore requires some mechanism of crustal thickening, commonly by sedimentation (to form buried basement of sedimentary furrows), magmatism (to form basement of oceanic arcs), or tectonic imbrication (to form ophiolite sequences and mélange belts). In the absence of such mechanisms, gravity and subduction can efficiently remove dense oceanic lithosphere from the crust. The crust of continental rifts, rhombochasms, sphenochasms, marginal basins, oceanic arcs, and remnant basins is susceptible to the crust-thickening mechanisms mentioned above and is, therefore, more abundantly preserved in orogenic belts than is normal ridge-generated oceanic crust.

The diagnosis of ensimatic tectonic elements within ancient orogens is difficult, but the composition of igneous rocks and other data can be related to basement composition. The composition of detritus can also indicate the nature and time of linkage of source blocks.

The sialic vs. simatic nature and extent of the initial basement of eugeosynclinal zones are highly varied and are dependent upon the evolution of the individual orogen in terms of geometry and nature of starting conditions, rifts, arcs, marginal and remnant basins, subduction zones, and strain history. The addition of oceanic and mantle materials to the continents by orogen accretion is complex due to the interaction and evolution of many processes. Single processes may be described but not single theories or finite models of orogenesis. Each orogen is a unique time-space collage of mappable elements, all generated, assembled, and rearranged by tectonic processes.

INTRODUCTION

The most interesting scientific questions invariably seem to deal with that which is just beyond our powers of observation. Such is true with the deep structure of orogenic belts, in particular the question of the nature and origin of the basement of eugeosynclinal blets. This question is fundamental to our understanding of orogenesis and crustal growth.

Eugeosynclinal belts have been identified as the sites of continental accretion, either because they rarely have any presumed basement exposed, or because the oldest exposed rocks are ophiolites or greenstones. If eugeosynclinal belts develop on preexisting sialic crust (ensialic), continental growth is dominantly vertical; this would be true if orogens are essentially tectonized continental shelf-slope-rise complexes. If eugeosynclinal belts are ensimatic, forming beyond continental margins on oceanic crust, then the continents have expanded laterally at the expense of ocean basins by accretion of eugeosynclines (Stille, 1941; Wells, 1949; Wilson, 1949; Kay, 1951; Drake and others, 1959; Dietz, 1963). According to plate tectonic concepts, both types of continental growth occur, although the problem remains to distinguish the tectonic elements, igneous rocks, and sediments of orogens that represent oceanic crust or upper mantle contributions (Dewey, 1969).

Stille (1941), Kay (1944), Wilson (1949), and Hess (1962) fully realized that a most important component of the eugeosyncline is the island arc. Few geologists realized the significance of this comparison or the need for rigorous study of island arcs. The great strides of marine geology, seismology, and volcanic geochemistry over the past decade have led to the new global tectonics (Isacks, Oliver, and Sykes, 1968) whereby island arcs and eugeosynclines are related to the motions of large crustal plates (Dewey and Bird, 1970).

There have been many recent attempts to integrate orogenic geosynclinal concepts with plate tectonics. Most of these attempts have been strongly inferential on the basis of limited new observations of Mesozoic and Cenozoic mountain belts rather than being strongly deductive on the basis of new critical observations of pre-Mesozoic orogeny. In fact, a greater reality seems to be attached to what may be called plate models of orogenic belts than to the belts themselves (Helwig, 1973). Plate tectonics is not yet a complete orogenic theory (Smith, 1971). The great contributions of legions of geologists who have worked in mountain belts are in danger of being cast aside (Trümpy, 1971), and there is a real need to rediscover old ideas and concepts as shown by White and others' 1970 reintroduction of the term subduction and by Hoffman's (this volume) use of "aulacogen." Perhaps this is rather like the biologists' need to rediscover Mendel sixty years ago. A major contribution of this book, and of the conference on which it is based, should be its emphasis on the significance of past and future research in mountain belts as a means of contributing to tectonic theory.

Two unifying concepts of orogenic theory are tectonic elements and tectonic processes. The ultimate driving forces of plate motions and mountain building (McKenzie, 1972) are presently unknown. This paper proposes that the initial nature and distribution of basement types are correlated with the initial and subsequent differentiation of tectonic elements and with the sequence of tectonic processes affecting the elements during the evolution of mountain belts. Thus, we may conclude that knowledge of initial basement, especially "zones of geosynclinal systems which can be demonstrated to have been initiated directly on an oceanic crust" (Khain, 1972, p. 211), is of fundamental importance in describing and understanding orogenic belts. A conception of orogenic belts as collages of basement-controlled tectonic elements may be considered as an extremely useful approach toward description and understanding of orogens. It must be understood, nevertheless, that the ultimate origins of tectonic elements, and of the sequence of tectonic processes whereby they are assembled, is a problem beyond present skills and knowledge.

ACKNOWLEDGMENTS

This paper is contribution no. 94 of the Department of Geology, Case Western Reserve University. I am grateful to my colleagues and students, especially Frank Stehli, Alan Nairn, and Steve Franks for providing a stimulating environment for thinking. I owe a great debt to Marshall Kay for inspiring and encouraging this work, and also to Robert Dott and the conferees for insights into geosynclines relative to plate tectonics. Ian Dalziel's comments contributed substantially to the final revision of this paper. The interpretations are mine.

NATURE OF TECTONIC ELEMENTS IN OROGENIC BELTS

Even an untutored but careful observer may note that mountain chains contain parallel elongate zones of contrasting topography and lithology. These I call tectonic elements. They are an intrinsic feature of mobile belts. Tectonic elements have many names, for example, belts, units, zones, isopic zones (Aubouin, 1965), and assemblages (Monger, Souther, and Gabrielse, 1972). (See King, 1969, p. 1–30 for discussion.) Tectonic elements here may be defined as mostly elongate regions of relatively homogeneous deformational, igneous, sedimentary, and metamorphic history as contrasted to adjacent elements within a mountain belt. The essence of a tectonic element is continuity in space and time, but a given tectonic element may be either a composite or a distinct part of several superposed elements representing a temporal progression and (or) a spatial migration. Similarly, tectonic elements may be recognized on different scales. Thus, the term "eugeosyncline," or "eugeosynclinal belt," is admitted to include many smaller tectonic elements (Kay, 1951).

This concept of continuity, in structure, stratigraphy, metamorphism, and in plutonism, is evident in every published map and paper concerned with mountain belts, and it demonstrates the need for simultaneous solving of many problems when studying orogenic belts. Whatever the scheme of subdivision, contrasts of tectonic elements are real. For example, structural units coincide with stratigraphic units, and element boundaries often prove to be major faults (Borukayev, 1970), all of which demonstrates fundamental contrast between adjacent elements in space and time.

If tectonic elements are universal features of mountain belts, one immediately reasons that, if similar elements are found in different mountain belts and if their spatial and temporal relations are similar, it is possible to formulate a general descriptive theory of mountain bulding, a theory of the orogenic cycle. Such reasoning underlay all orogenic theories until the time of

plate tectonics (Co
an attempt to prov
mountain belts on
(Hall, 1859), crust
formation (Kober,
1941), but strong
determinative role
gantly proposed by

With the advent
objective of orog
establish the relati
that were so beau
geologists and the
elements that wer
lated to plate mo
1969; Bird and D

TECTONIC ELE
REAL

A summary co
have been define
orogenic syntheses
overlapping mean
terms applied to it.
identified only in
cient. That all i
elements have bee
that more than t
type of element
trasting geologica
tural levels is equ

Three observat
ments exist:

(a) The first c
prises those eleme

	Tectonic
A.	Oceanic arc*
	Cordilleran arc
	Detached arc
	Pericratonic for
	Successor basin
	Miogeocline
B.	Marginal basin*
	Arc-trench gap*
	Trench*
	Rift basin*
	Aulacogen
	Miogeoclinal ri
	Eugeanticlinal
	mentary inacti
	Microcontinent
	Midocean ridge
	Oceanic island*
	Sphenochasm*
	Rhombochasm*
	Remnant sea*

Asterisk indica

Vestern Reserve
y colleagues and
hli, Alan Nairn,
ng a stimulating
we a great debt
and encouraging
Dott and the con-
clines relative to
comments con-
al revision of this
mine.

LEMENTS
LTS

ful observer may
contain parallel
topography and
ic elements. They
bile belts. Tectonic
for example, belts,
ubouin, 1965), and
er, and Gabrielse,
30 for discussion.)
e defined as mostly
homogeneous de-
entary, and meta-
d to adjacent ele-
. The essence of a
in space and time.
t may be either a
of several super-
a temporal progres-
igration. Similarly,
ognized on different
eugeosyncline," or
dmitted to include
nts (Kay, 1951).
, in structure, stra-
d in plutonism, is
nap and paper con-
and it demonstrates
lving of many prob-
ic belts. Whatever
contrasts of tectonic
ple, structural units
units, and element
o be major faults
which demonstrates
en adjacent elements

universal features of
ately reasons that, if
l in different moun-
ial and temporal re-
ssible to formulate a
of mountain bulding.
ycle. Such reasoning
ies until the time of

plate tectonics (Coney, 1970). Each theory was an attempt to provide a general explanation of mountain belts on the basis of sedimentation (Hall, 1859), crustal nature (Haug, 1900), deformation (Kober, 1928), or magmatism (Stille, 1941), but strong emphasis was given to the determinative role of geosynclines (e.g., as elegantly proposed by Aubouin, 1965).

With the advent of plate tectonics, the major objective of orogenic synthesis has been to establish the relation between tectonic elements that were so beautifully analyzed by orogenic geologists and the Mesozoic-Cenozoic tectonic elements that were inferred to be clearly related to plate models (Mitchell and Reading, 1969; Bird and Dewey, 1970).

TECTONIC ELEMENTS: PLATE MODELS VS. REAL MOUNTAIN BELTS

A summary comparison.—Tectonic elements have been defined in both plate models and orogenic syntheses. Each element, therefore, has overlapping meanings and commonly has two terms applied to it. Some elements can be clearly identified only in the modern, others in the ancient. That all important species of tectonic elements have been recognized is uncertain, and that more than two terms exist for the same type of element exposed or preserved in contrasting geological contexts or at different structural levels is equally unclear.

Three observational classes of tectonic elements exist:

(a) The first class of tectonic elements comprises those elements that are recognized clearly in both active tectonic environments and ancient orogenic belts, but it includes nonorogenic elements. This class includes tectonic elements formed at consuming plate margins, accreting plate margins, midplate positions, and at post-orogenic successor basins (table 1, A).

(b) The second class of tectonic elements encompasses those elements that probably are identified correctly in both active and inactive orogenic belts, but these may evoke dispute. This class includes a variety of tectonic elements: trenches, marginal basins, midocean ridges, miogeoclinal and eugeoclinal ridges, and paired metamorphic belts (table 1, B).

(c) The third class of tectonic elements comprises those elements which are attributed to plate models or are found in mountain belts but not both. These elements are significant, but often elusive, and further work should be done in order that we may better recognize them. Tectonic elements of this kind in plate models include the sediment prism of the ensimatic continental rise, the ocean floor itself, the outer sedimentary arcs of island arcs, and the East Indies-type of isolated small ocean basin. Tectonic elements that are difficult to identify in plate models but that are obvious in orogenic belts include, for example, deep-water ensialic foredeep furrows, nappes, and gneiss-dome belts. In addition, tectonic elements of questionable definition or smaller scale exist that are not considered here. Many tectonic elements in orogenic belts may be unique to the extent that they possess a polyphase history.

Resolving the differences.—The complexity of

TABLE 1.—TECTONIC ELEMENTS INCORPORATED INTO OROGENIC BELTS

Tectonic element	Young example	Other possible or probable terms
A. Oceanic arc*	Tonga arc	Island arc, eugeosyncline
Cordilleran arc	Andes arc	Same
Detached arc	Japan arc	Same
Pericratonic foredeep	Andean foredeep	Exogeosyncline
Successor basin	Great Valley, California	Epieugeosyncline
Miogeocline	Atlantic coastal plain	Paraliageosyncline, miogeosyncline
B. Marginal basin*	Philippine Sea	Eugeosyncline, small ocean basin
Arc-trench gap*	?	Eugeosyncline, high P/T belt
Trench*	Tonga Trench	Eugeosyncline, high P/T belt
Rift basin*	East African Rift, Red Sea	Taphrogeosyncline
Aulacogen	Benue Trough	Taphrogeosyncline
Miogeoclinal ridge	Outer basement ridge, Atlantic shelf	Barrier en creux
Eugeanticlinal ridges* sedimentary inactive arc	Andaman arc, New Hebrides	Tectonic and eugeanticlinal ridges
Microcontinent	Corsica	Block
Midocean ridge*	Iceland	
Oceanic island*	Hawaii	
Sphenochasm*	Bay of Biscay	Small ocean basin
Rhombochasm*	Cayman Trough	Eugeosyncline, small ocean basin
Remnant sea*	Black Sea	Small ocean basin

Asterisk indicates elements with oceanic basement or partly oceanic basement.

TABLE 2.—FEATURES OF BOUNDARIES OF TECTONIC ELEMENTS

Essential feature	Major (plate) boundaries			Examples, boundaries of other tectonic elements		
	Accreting	Consuming	Transform	Marginal basin	Ocean arc	Pericratonic foredeep
Subduction		+			+	
Normal faulting	+			+	+	
Strike-slip fault		+	+			
Obduction/thrusting		+		+	+	+
Truncation of tectonic trends	+	+	+			
High P/T metamorphism		+				
Ophiolite	+	+		+	+	
Bounds plutonic arc		+		+	+	
Bounds shelf deposits	+					+
Bounds pelagites		+		+		
Bounds submarine fans	+	+		+		+
Bounds flysch		+		+		+
Bounds molasse	+	+	+	+		+

assembled and crushed tectonic elements comprising each mountain belt has led to a complex terminology for classifying tectonic elements. Many terms overlap or have multiple meanings, and some definitions have changed or lost meaning with time and usage (Coney, 1970). Plate-model terminology for tectonic elements that is based upon use of specific named active tectonic elements as analogues appears to offer a relatively objective descriptive and genetic framework for classification and is recommended. However, there are several reasons why an eclectic terminology retaining old purely descriptive terms (table 1) should be maintained. (See Khain, 1972, and Zonenshain, 1972, for other views.)

The first reason is ignorance. Much is yet to be learned of the presently active mountain belts before they can be characterized and causally related to plate motions and (or) other tectonic processes (Gilluly, 1972).

The second reason is time, as related to orogeny. In order to understand tectonic elements, progressive stages of development at different structural levels of exposure must be known. Hence the study of deeply eroded ancient mountain belts must be integrated with study of young tectonics.

The third reason is that tectonic elements may be polygenetic (table 1). There may be several generative settings for similar classified tectonic elements and their sediments. For example, flysch nappes may be elements of foredeep troughs that originated as marginal basin fill, or continental rise fill, or perhaps by some other means. Thus, generic classification of a tectonic element may omit, clarify, or obscure its origin.

Resolving differences of terminology depends on new knowledge, critically gathered. New syntheses of orogenesis hopefully should be biased neither toward so-called "plate models" as has been true recently (Helwig, 1973), nor toward the locally conceived frameworks of orogenic specialists (e.g., Aubouin, 1965). In this context, it would be useful to consider a collage concept of orogenesis whereby orogenic evolution consists of the bringing together of diverse tectonic elements without regard to ruling theories, but by employing identified young analogs and the principles of plate tectonics. This concept is considered further at the end of this paper.

Nature of boundaries of tectonic elements.—The largest scale tectonic elements of the earth's crust are the rigid plates as conceived in the new global tectonics (Le Pichon, 1968; Isacks, Oliver, and Sykes, 1968). Seismology has shown that the boundaries of these plates include fault systems of three types: rifts, oceanic underthrusts (i.e., subduction zones), and strike-slip or transform faults. Hybrid rift-transform and underthrust-transform boundaries are also possible (Harland, 1971).

Tectonic elements of orogenic belts have contrasting rock suites and structure and are always topographically distinguished from adjacent elements (table 2). These features immediately suggest that the boundaries between tectonic elements are major faults or abrupt flexures. This proposition may be verified by examining any zonal subdivision or historical interpretation of a mountain belt.

The boundaries of the largest scale tectonic elements of orogenic belts are therefore the likely sites of defunct plate boundaries. The

boundary between
geosynclinal belts
faulted, but it may
ment-filled margin
(e.g., Churkin, th
edge broken at
(Dietz, 1963; Rod
1970). The bound
held by sialic mic
similarly faulted
Sardinian block i
tine belts, attenda
tonic lines have
trenches and su
1971). Transform
vergent plate boun
ones. In both situa
nation of orogenic
plained by such f
p. 1049–1050); Ho

The topographi
elements in their f
the remnant arcs,
arcs of the wester
generally been e
(Mitchell and Rea
sedimentary contr
ments both contro
The boundaries o
of facies change,
pelagic sediments
dites to bathyal o
and pelagites. Ru
sized the persiste
block structure of

The relative p
may change with t
the establishment
provenance linka
elements in effect
behave as indepe
not only fault b
translated or trans
Gabrielse, 1972).
be difficult to esta
are preserved wit
(e.g., Kay and C
volume; Crowell,

The persistent,
tectonic elements
orogenesis probab

The basement o
ment" I mean cru
the example of i
the initial stages
genesis. Implicit i
tion that orogenes
ing the shifting

boundaries of other ›mic elements	
Ocean arc	Pericratonic foredeep
+	
+	
+	+
+	
+	
	+
	+
	+
	+

f terminology depends
:ically gathered. New
hopefully should be
-called "plate models"
' (Helwig, 1973), nor
·ed frameworks of oro-
ubouin, 1965). In this
ıl to consider a collage
ıereby orogenic evolu-
ıng together of diverse
regard to ruling theo-
entified young analogs
te tectonics. This con-
er at the end of this

ɔf *tectonic elements.*—
elements of the earth's
:s as conceived in the
: Pichon, 1968; Isacks,
Seismology has shown
ese plates include fault
rifts, oceanic under-
zones), and strike-slip
›rid rift-transform and
›undaries are also pos-

rogenic belts have con-
:ructure and are always
›hed from adjacent ele-
features immediately
ıries between tectonic
lts or abrupt flexures.
verified by examining
ıistorical interpretation

: largest scale tectonic
elts are therefore the
plate boundaries. The

---

boundary between the eugeosynclinal and miogeosynclinal belts of orogens is generally thrust faulted, but it may represent the edge of a sediment-filled marginal basin having oceanic crust (e.g., Churkin, this volume) or a continental edge broken at an accreting plate margin (Dietz, 1963; Rodgers, 1970; Dewey and Bird, 1970). The boundaries of cordilleran ridges upheld by sialic microcontinental blocks would be similarly faulted as has been shown for the Sardinian block in the Mediterranean. Serpentine belts, attendant mélanges, and median tectonic lines have been attributed to ancient trenches and subduction zones (Dickinson, 1971). Transform faults may be attached to convergent plate boundaries as well as to divergent ones. In both situations, the abrupt strike termination of orogenic tectonic elements may be explained by such faults (Bird and Dewey, 1970, p. 1049–1050); Hoffmann, this volume).

The topographic differentiation of tectonic elements in their formative stages, for example, the remnant arcs, marginal basins, and active arcs of the western Pacific (Karig, 1971), has generally been explained by block faulting (Mitchell and Reading, 1971). The igneous and sedimentary contributions to these tectonic elements both control and reflect the topography. The boundaries of the elements are thus zones of facies change, for example, from volcanic to pelagic sediments or from submarine fan turbidites to bathyal or abyssal plain finer turbidites and pelagites. Russian geologists have emphasized the persistent, so-called deep faults and block structure of geosynclines (Peyve, 1945).

The relative positions of tectonic elements may change with time. In ancient orogenic belts, the establishment of sedimentary facies and provenance linkages between adjacent tectonic elements in effect establishes that they do indeed behave as independent blocks at times and are not only fault bounded but also differentially translated or transported (Monger, Souther, and Gabrielse, 1972). Linkages between blocks may be difficult to establish unless transitional facies are preserved within or adjacent to fault zones (e.g., Kay and Crawford, 1964; Eisbacher, this volume; Crowell, this volume).

The persistent, consistent differentiation of tectonic elements during contrasting phases of orogenesis probably reflects basement contrasts.

The basement of tectonic elements.—By "basement" I mean crustal rocks formed prior to (in the example of inherited basement) or during the initial stages of (generative basement) orogenesis. Implicit in this definition is the assumption that orogenesis is episodic, probably involving the shifting of crustal consumption from one plate boundary to another (Mitchell and Reading, 1969).

An attractive interpretation is that contrasting tectonic elements are underlain by contrasting basement rocks because tectonic differentiation implies deep-seated causes. Also, there are data justifying this view.

Detailed geophysical surveys have established that the crust of stable continental margins changes over a distance of several tens of kilometers from thick typically continental sialic crust to thin simatic oceanic crust in the vicinity of the continental rise (Drake and others, 1959). Even stronger and more abrupt crustal changes take place across Pacific-type continental margins. Oceanic arcs show a twofold to fourfold thickened oceanic crust separating typical oceanic crust on the trench side from volcanic and sedimentary-thickened transitional oceanic crust of the marginal basin behind the arc (Karig, 1971; Vogt, Schneider, and Johnson, 1969). Comparable geophysical contrasts are preserved in young orogenic belts that have been thoroughly studied (Thomspon and Talwani, 1964).

It is not possible, however, to compare unambiguously geophysical data for *ancient* orogens, that have undergone complex polyphase history and intense crushing followed by stress relaxation and isostatic adjustment. More indirect evidence may be used to evaluate basement (see farther on). To understand continental growth and fragmentation, our principal problem is to recognize tectonic elements within orogens and to evaluate their basement. The fate of tectonic elements depends upon the interaction of basement, cover, and tectonic processes.

NATURE OF TECTONIC PROCESSES

Principles of orogenic tectonics.—Orogenic belts are belts of crustal shortening. The principal tectonic consequences of this shortening are folding, crustal thickening, and transport of orogenic zones toward stable forelands. Seismology, paleomagnetism, and structural studies have confirmed that processes other than shortening are also significant: longitudinal displacements (strike-slip faulting), lateral displacements involving the removal of crustal material from below (subduction), large-scale rotations, and lateral displacements involving extension. These displacements are not mutually exclusive (Packham and Falvey, 1971; Harland, 1971).

Displacements.—The potential magnitude of crustal displacements between elements within orogens is fantastic considering that all pre-Mesozoic oceanic crust has apparently been consumed or incorporated in orogenic belts and circum-Pacific subduction zones. Hence, crustal blocks may be transported from one continental block to another, and island arcs and microcontinents may be swept in, so to speak, to an orogenic belt (Wilson, 1967; Dewey and Bird, 1970). Large displacements may also occur across transcurrent faults. Large rotations and crustal extension may accompany lateral displacements as indicated for the Mediterranean region (Smith, 1971; Hsü, 1972). Crustal extension may occur within successor basins (Eisbacher, this volume), possibly proceeding so far as to form marginal seas with a new ocean crust (Packham and Falvey, 1971). The separation of closely related tectonic elements and the juxtaposition of tectonic elements formed hundreds or even thousands of kilometers apart is possible, therefore, and consequently necessitates extremely abrupt changes in basement, sedimentary cover, magmatism, metamorphism, fossils, paleomagnetism, and paleoclimatology from one tectonic element to another (Wilson, 1966; Monger, Souther, and Gabrielse, 1972; Helwig, 1972; Ernst, 1973). The arrival of a displaced or newly generated block is marked by sedimentary-erosional linkage with its neighbor (Monger, Souther, and Gabrielse, 1972). If two tectonic elements exhibit sharply disjunctive histories, their boundary is probably a transcurrent fault, deep normal fault or suture belt, or some superposed combination thereof.

The more traditional types of displacement in orogens may also be considerable. The Alpine nappes are tectonic elements showing considerable absolute and relative displacement and may be reconstructed in time and space by establishing facies-paleogeographic linkages (Trümpy, 1960). Displacement could be especially great if thrust sequences are transported across suture belts (Oxburgh, 1972) or transcurrent faults. Thrust transport may preserve tectonic elements in such manner that they commonly are bottomless, lacking part or all of their basement, but they could also be topless. In either event, thrust sequences could preserve tectonic elements that might otherwise have been lost to view by subduction.

Plate-tectonic orogenic models (Dewey and Bird, 1970) have emphasized the ordered, organized spatial-chronological development of orogenic belts, as have nearly all orogenic theories. However, recent studies (e.g., Monger, Souther, and Gabrielse, 1972; Gastil and others, 1972) have emphasized the disordering potential of tectonic processes. Regretfully, the reductionist approach toward orogenic theory, including plate tectonics, by emphasis on ordering processes has left little room for recognition that tectonic elements in mountain belts may be highly disordered in anything other than highly complex palinspastic-chronological frameworks. Evidently, an important consequence of displacements is that tectonic elements become disordered with respect to simple plate tectonic models (fig. 1).

Crustal thickening and crustal loss.—Crustal thickening is one essential property of mountain belts (Eisbacher, this volume). In orogenic belts crustal thickening is produced by mechanical, sedimentary, or magmatic means. Compressive stress across an orogen mechanically thickens its crust by ductile flow, folding, and thrust and reverse faulting: uplift above sea level is accompanied by physical depression of the Moho. Oceanic underthrusting could accrete seaward and (or) underplate an orogen with any type of tectonic element, including ocean crust and sediments and continental or microcontinental blocks. Sedimentary thickening occurs in geosynclines, particularly in the flanking clastic wedges of oceanic and cordilleran arcs, but also in furrows and successor basins between eugeoanticlinal ridges and in pericratonic foredeep troughs. The arcs themselves and their pyroclastic and erosional products may more appropriately be considered as juvenile magmatic contributions to eugeosynclinal belt thickening (Dickinson, this volume).

In any place that geosynclinal thicknesses of sediments accumulate, crustal thickening is occurring, and thus miogeoclines, marginal basins, and even rift basins, transcurrent pullapart basins (Crowell, this volume), and Bahama-type platforms are all tectonic elements thickened by sedimentation. (Note that these regions commonly are attributed to oceanization by some schools of geology.) Any of them may be incorporated into orogenic belts. The pulling apart of continental crust seems involved in all of these tectonic elements. Extension of this crust does not involve actual loss, but only thinning and subsidence due to coupling of sial to new oceanic crust (Bott 1971). There is no real oceanization, but rather a stretching of continental crust. Eventually, subsided semioceanic areas will accumulate great thickness of sediment (Hutchinson and Engels, 1972). Hence, real crustal thickening by volcanism and chemical sedimentatiönn occurs; these rocks may be incorporated into orogens during subsequent compression (Trümpy, 1971). Similarly, the pulling apart of marginal seas forms a deep sediment trap, the potential site of threefold thickening of oceanic crust by sedimentation (Packham and Falvey, 1971).

So-called "crustal loss" in compressed oro-

---

genic belts likev
thickening or rec
misleading phras
two types of pre
low and one fro
it involves drivi
orogens, yields n
cal thickening o
other types of
lower density tl
tribute to thicke
derthrusting, an
overthrusting an
presumed loss, fr
outward gravity
root. These pro
tribute the thicke
although admitte
sion products co
geoclines, such a
gal cone, if fore
ping sediment. T
been called crust
the high-pressure
belt above the s
tion at a given t

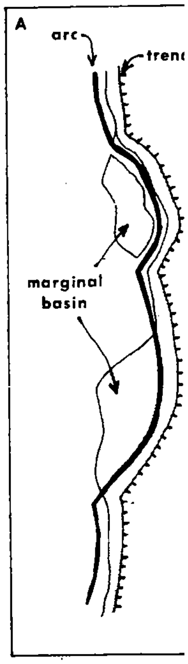


FIG. 1.—A simp
A, Development o
Lateral displacem
transform fault us
some regions; no
crustal convergen
occurs at continen

n belts may be
other than highly
ical frameworks.
ence of displace-
nts become dis-
le plate tectonic

tal loss.—Crustal
erty of mountain
e). In orogenic
luced by mechan-
means. Compres-
echanically thick-
olding, and thrust
bove sea level is
pression of the
ng could accrete
n orogen with any
iding ocean crust
al or microconti-
ckening occurs in
he flanking clastic
ran arcs, but also
sins between eu-
cratonic foredeep
and their pyro-
may more appro-
ile magmatic con-
belt thickening

nal thicknesses of
thickening is oc-
, marginal basins,
rent pullapart ba-
and Bahama-type
ents thickened by
ese regions com-
nization by some
them may be in-
elts. The pulling
ms involved in all
Extension of this
oss, but only thin-
oupling of sial to
). There is no real
retching of conti-
sided semioceanic
thickness of sedi-
ls, 1972). Hence,
canism and chemi-
ese rocks may be
luring subsequent
). Similarly, the
eas forms a deep
site of threefold
by sedimentation
.
compressed oro-

---

genic belts likewise mostly constitutes crustal thickening or redistribution. To understand this misleading phraseology, consider that there are two types of presumed loss, one kind from below and one from above. Plate consumption, if it involves driving out of ocean crust below orogens, yields melts to produce overall chemical thickening of orogenic crust. If it involves other types of tectonic elements, they are of lower density than the mantle and thus contribute to thickening by seaward accretion, underthrusting, and underplating, or perhaps by overthrusting and obduction. The second type of presumed loss, from above, involves erosion and outward gravity gliding from the orogenic root. These processes serve merely to redistribute the thickened crustal mass of the orogen, although admittedly a considerable loss of erosion products could occur to build distant miogeoclines, such as the Mississippi delta or Bengal cone, if foredeeps are not efficient in trapping sediment. The principal effect of what has been called crustal loss may well be to produce the high-pressure, low-temperature metamorphic belt above the suture zone of crustal consumption at a given time.

From the discussion above and from knowledge of the history of mountain belts, we may conclude that the development of the continental crust is an essentially irreversible process (Mouratov, 1972). Such irreversibility is attributed to the inherent buoyancy and volatile geochemistry (following many authors) of continental crust. These factors also place an upper limit on maximum thickness of continental crust (Fyfe, 1973). Oceanization (Van Bemmelen, 1969) is viewed as more of a semantic than geologic problem (Trümpy, 1971, p. 312). The thinning of continental crust in one region is inevitably accompanied by its thickening or redistribution elsewhere.

Effects of orogenic processes: summary.—The principal effect of orogenic processes is to generate what is called the granitic layer of the earth's crust, such generation being an irreversible process (Peyve and others, 1972). The genesis of tectonic elements involved is initially in some orderly spatial-chronological sequence; but continuing orogenesis may modify, disperse, reassemble, and strain tectonic elements to yield a consolidated orogenic belt that often is extremely difficult to decipher. Crustal shortening,

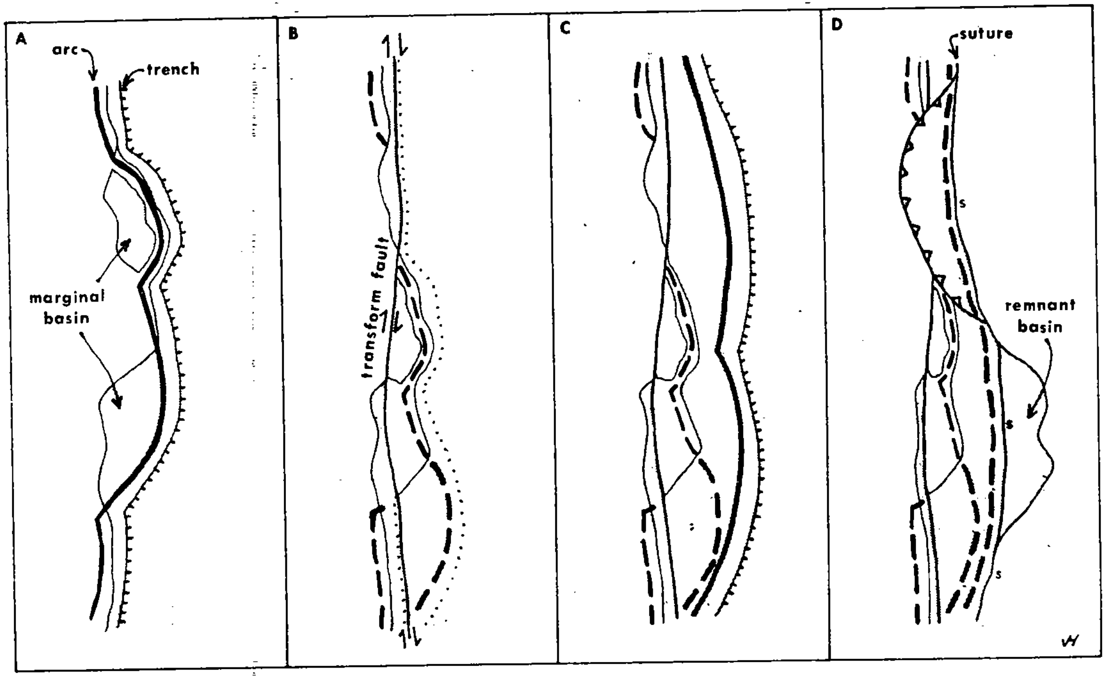


Fig. 1.—A simple hypothetical example of an orogenic collage (shaded areas are underlain by oceanic crust). A, Development of subduction zone (trench) and orderly arrangement of related arcs and marginal basins. B, Lateral displacement; initial configuration of arcs, basins, and sediment-source linkages becomes disordered; transform fault uses preexisting line of weakness (subduction zone dotted line) to produce hybrid structure in some regions; note also omission and repetition of inactive arc (dashed line) due to faulting. C, Renewed crustal convergence; a new arc and trench are formed. D, Continental collision; obduction of tectonic elements occurs at continental salient, and remnant basin forms in continental recess.

thickening, and suturing are perhaps the most important effects of tectonic stresses, particularly as they lead to termination of old generative configurations and to beginning of new ones (e.g., new arcs, new subduction zones, plate flips, and conversion to transform boundaries). Such changes inevitably lead to hybrid structures. In particular, the boundaries of tectonic elements are anisotropies likely to be reactivated under tension, compression, and shear. Consequently, it is profitable to think of major structural boundaries as superposed transcurrent faults, subduction zones, and normal faults.

Any change in plate-margin movement or process is potentially a disordering process with regard to an existing configuration of tectonic elements. Oceanic crust and sediments seem particularly susceptible to complete disordering to the point of mélange (Peyve, 1969; Hsü, this volume).

At convergent plate margins, gravity can act to remove efficiently the dense oceanic lithosphere by subduction. Oceanic remnants also could be preserved by favorable geometry by cover of thick sediments, by cover of oceanic arcs or volcanoes, or by tectonic imbrication (see farther on). Conversely, gravity forces spread thickened rising orogens by erosion and outward thrusting, thereby producing displacement and strain of assembled tectonic elements and, ultimately, more uniform crustal thickness in response to isostasy.

Orogenic processes are thus simultaneously ordering and disordering processes, and the longest lived orogenic belts are rationally seen as the most disordered; that is, as a *collage*, or collection of diverse crustal elements complexly assembled (fig. 1). By fully investigating tectonic processes and tectonic elements, we have the means to understand orogenic collages. The most important features of orogens are tectonic elements, their boundaries, and their mutual relations through time as established by linkages and disjunctions of igneous, metamorphic, sedimentary, and structural events. Paleontology, geochronology, and paleomagnetism are important tools of stratigraphic-structural studies needed to establish linkages. A knowledge of the nature and age of the basement rocks in each tectonic element is most critical perhaps to establish the locale of origin of the element and to allow evaluation of the evolution of the earth's crust in terms of the kinematics of plates, history of individual tectonic elements, and of mechanics of continental growth.

KEY ROLE OF BASEMENT

It can be argued that basement contrast, in terms of gross composition of crust, has little influence upon inception of orogenic belts because convergent plate boundaries are not all located at continental margins (Dott, this volume). (Presumably, inception of an orogenic belt requires plate convergence by definition.) This is conceivably true in terms of the initial spatial position of arcs which contribute new sialic material to the crust; however, the work of Karig (1971), Matsuda and Uyeda (1971), and Packham and Falvey (1971) shows that the western Pacific arcs have migrated away from the Australian and Asian land masses, as originally suggested by A. Wegener, demonstrating that the oceanic positions of these arcs are secondary.

Furthermore, if continental edges originate by rifting, they must be the loci of oldest ocean crust that is also the coolest, most dense, and topographically lowest (Sclater and others, 1971). Hence, continental edges are the sites of minimum energy input required for onset of subduction. Conversely, initiation of subduction within continents is highly unlikely, and, in fact, continental suturing halts convergence.

Whether basement contrasts exert a role in the siting of extensional and transcurrent boundaries within orogens is debatable. The San Andreas Fault appears to ignore, so to speak, the boundary of Franciscan and Sierran basement (Gastil and others, 1972). On the other hand, the Appalachian-Caledonian belt certainly determined the site of opening of the North Atlantic Ocean. In Eurasian mountain chains, the repeated activation of deep faults is noteworthy (Khain, 1972).

Orogenic belts are incorporated into the continents by being crushed between or against continental basement cratonic blocks. In this respect, the fate of all tectonic elements is predestined. At every stage of development between the generative and terminal stages of orogenic evolution, the type of crust, including both cover and basement rocks composing each tectonic element, plays a key role in determining its history.

Ensimatic versus ensialic tectonic elements.—The stable regions of the earth's crust are of two types (Dietz, this volume): oceanic and continental. They are each remarkably homogeneous from a geophysical point of view, and each has distinctive thickness and composition that is reflected in mean elevation and sedimentary accumulation.

Orogenic belts are the unstable regions of the earth's crust that are characterized by geophysical, compositional, and topographic diversity. For active orogens, the delineation of ensimatic and ensialic tectonic elements is possible by di-

---

rect geological and g
These belts are the
two end-member cru
tonic processes. By
geologic evidence, it
tonic elements do occ
must behave much c
ments because their
density, and thus th
properties as well, a

The general eff
through geologic ti
to add modified or t
tinents. The added
assemblage of defo
survive orogenic p
must generally hav
Any sizable tectoni
sentially unaltered
served in orogenic
subduction can effic
lithosphere from co
sizeable tectonic ele
or sialic crust, that
sity not exceeding
comes incorporated
compositional and
they cannot be mac
asthenosphere. It
sider that such ele
cause the silica an
melt and rise agai
level. Nevertheless
fied or sialic crust
if thinned by exten
ducted by couplin
plates, which woul
plating and in grea
strated in the Him
1972).

In summary, oc
ably modified to
ensimatic tectonic
of modification ar
mechanical thicke
ensimatic tectonic
belt, which repres
tinental growth
record of the ear
deeply subsided a

Ensimatic tecto
simatic tectonic
mains in an orog
by oceanic crust
inherited essentia
period of format
currence of ocea
served in orogen

crust, has little
nic belts because
not all located
volume). (Pre-
nic belt requires
.) This is con-
tial spatial posi-
new sialic ma-
e work of Karig
971), and Pack-
that the western
y from the Aus-
s originally sug-
strating that the
s are secondary.
edges originate
i of oldest ocean
most dense, and
ter and others,
s are the sites of
ed for onset of
on of subduction
nlikely, and, in
convergence.
exert a role in
anscurrent boun-
atable. The San
ore, so to speak,
nd Sierran base-
2). On the other
ian belt certainly
of the North At-
untain chains, the
ults is noteworthy

ated into the con-
en or against con-
locks. In this re-
elements is pre-
development be-
inal stages of oro-
ust, including both
mposing each tec-
le in determining

ctonic elements.—
rth's crust are of
me): oceanic and
remarkably homo-
point of view, and
s and composition
levation and sedi-

able regions of the
erized by geophysi-
ographic diversity.
eation of ensimatic
s is possible by direct geological and geophysical study (table 1). These belts are the sites of modification of the two end-member crustal types by means of tectonic processes. By actualistic principles and geologic evidence, it is clear that ensimatic tectonic elements do occur in ancient orogens. They must behave much differently than ensialic elements because their thickness, composition, and density, and thus their mechanical and thermal properties as well, are greatly different.

The general effect of orogenic processes through geologic time has been to thicken and to add modified or totally new crust to the continents. The added strips constitute a diverse assemblage of deformed tectonic elements. To survive orogenic processes, tectonic elements must generally have a thick low-density cap. Any sizable tectonic elements composed of essentially unaltered oceanic crust cannot be preserved in orogenic belts because gravity and subduction can efficiently remove dense oceanic lithosphere from consuming plate margins. Any sizeable tectonic elements composed of modified or sialic crust, that is, crust having mean density not exceeding about 2.8 to 2.9 gm/cc, becomes incorporated into orogens because their compositional and density contrast assures that they cannot be made to sink into the underlying asthenosphere. It is also unreasonable to consider that such elements could be oceanized because the silica and alkali content could readily melt and rise again to maintain a high crustal level. Nevertheless, tectonic elements of modified or sialic crust possibly could subside deeply if thinned by extension or could be partially subducted by coupling to descending lithosphere plates, which would result in continental underplating and in great crustal thickening as demonstrated in the Himalaya and the Andes (Plafker, 1972).

In summary, oceanic crust must be considerably modified to survive orogenic processes as ensimatic tectonic elements. The principal means of modification are igneous and sedimentary and mechanical thickening. Therefore, the area of ensimatic tectonic elements within an orogenic belt, which represents the best estimate of continental growth and also contains the limited record of the earlier ocean basins, tends to be deeply subsided and (or) difficult to recognize.

Ensimatic tectonic elements: definition.—Ensimatic tectonic elements are those crustal domains in an orogenic belt which are underlain by oceanic crust generated during orogenesis or inherited essentially unmodified from an earlier period of formation. Table 3 lists types of occurrence of ocean crust; all types could be preserved in orogenic belts. Preservation of ocean crust is possible either in outcrop as ophiolite or mélange suites or at depth under cover of stratigraphically or structurally higher rock sequences.

The definition of ensimatic tectonic elements entails a semantic problem related to the inherently allochthonous character of an orogenic collage. The joining of sialic blocks along a suture zone involves squeezing out of materials. Ensimatic tectonic elements may be subducted or obducted (overthrust), or ocean crust and its cover may be tectonically separated. Ensialic tectonic elements may be similarly allochthonous. Ultimately, a mountain chain thereby may become entirely ensialic but still incorporate many ensimatic tectonic elements or sedimentary sequences initially ensimatic (for example, in accord with Gansser's interpretation of the Himalayan belt, 1966, and Glennie and others interpretation of the Oman Mountains, 1973). It is difficult to conceive of the intense deformation and crustal shortening involved in the nappe structure of the Alpine-Himalayan belt unless squeezing out of oceanic domains occurred (Trümpy, 1971). In addition, if oceanic crust can be thrust over continental rocks, it seems even more probable that continental blocks could be thrust over oceanic crust; the degree of allochthony of sialic basement blocks within orogens (Peyve, 1969) is problematical.

Therefore, it appears necessary to qualify the ensimatic nature of a tectonic element as being allochthonous where tectonically transported over ocean crust and as being detached if inferred to be detached from an original oceanic basement. A tectonic element may thus be: (1) stratigraphically ensimatic (autochthonous on ocean crust), (2) an ensimatic detachment (or paleogeographically ensimatic, Lemoine, 1972), or (3) structurally ensimatic (allochthonous). Condition 1 or 2 may also apply where condition 3 applies.

Ensimatic tectonic elements: recognition.—The identification of ophiolite sequences as oceanic crust seems reasonably well established on geophysical, geochemical, and petrologic grounds (Dewey and Bird, 1971; Pearce and Cann, 1971). However, information on the composition and sequence of modern ocean crust is inadequate to allow distinction of ophiolites generated at midocean ridges from those formed in marginal basins or in other places. Certain alpine-type peridotites and serpentinites may be confused with ophiolites (Chidester and Cody, 1972), and some ophiolites could speculatively represent the lower part of continental crust and adjacent upper mantle. Thus, the origin of some ultramafic sequences called "ophiolite" is disputable.

TABLE 3.—OCEANIC CRUST: ORIGIN AND OCCURRENCE IN OROGENS

Descriptive name	A. Origin and distinctive features (see table 1 for examples)
Rift	Crustal extension, incipient ocean crust formation; block faulting; prisms of clastic, carbonate and evaporite sediments; sialic detritus; peralkaline basalts
Sphenochasm	Crustal extension with rotation of sialic blocks, directly coupled to zone of compression; wedge-shaped ocean basin; submarine fans and turbidites; sialic detritus
Rhombochasm	Crustal extension limited by coupled transform faults; block faulting; submarine fans and turbidites; sialic detritus
Normal ocean basin	Prolonged development of first three above; pelagic oozes, cherts
Marginal basin	Crustal extension behind arc; block faulting; turbidites and tuffs; both pyroclastic and sialic detritus; alkali olivine basalts
Remnant basin	Remnant of normal ocean crust preserved between translated sialic blocks; passes into deformed rocks along strike; turbidites and restricted basin facies are postorogenic; sialic detritus
Ocean arc	Ocean crust preserved beneath arc volcanics
Oceanic island	Ocean crust preserved beneath Hawaiian-type volcanoes

Descriptive name	B. Occurrence in orogens	
	Nature of preservation	Example
Ophiolite sheet	Allochthonous, obducted (Coleman, 1971)	New Caledonia
Ophiolitic mélange (thalassogeosyncline)	High P/T metamorphism and accretion in subduction zones (Hamilton, 1969; Bogdanov, 1969)	Franciscan
Ophiolitic suture zone	Intense deformation in narrow belt	Indus suture
Ophiolitic cordillera	Compression without subduction or obduction (Gansser, 1973)	Western Cordillera of Colombian Andes?
Hidden beneath eugeosynclinal tectonic elements	Buried beneath thick sedimentary, volcanic, or structural cover	Central Newfoundland Appalachians
Subducted paleogeographic realms	Inferred to originally underlie allochthnous nappes, etc., but not preserved	Alpine belt

Review of the ophiolite problem is beyond the scope of this paper. The writer concurs with Coleman (1971) and Dewey and Bird (1971) that the origin of true ophiolite sequences is ocean crust and upper mantle, but more thorough studies of such rocks and their modern analogs undeniably are needed.

The problem at hand is to evaluate the basement of tectonic elements where basement is not exposed or where perhaps only the uppermost part of an ophiolite sequence is exposed. That eugeosynclinal furrows (Aubouin, 1965) are the most extensive ensimatic fraction of orogenic belts seems likely. This inference follows from consideration that most oceanic crust of the geologic past has vanished without a trace (Smith, 1971), and the sutures marking its disappearance (subduction zones) are subsident by nature. The effect of relative buoyancy buries these oceanic sutures in sediments that are derived from rebounding sialic terranes (Ernst, 1973).

Some plausible approaches to evaluation of the basement of eugeosynclinal tectonic elements are designated (a) through (f) in the discussions that follow. An effort is made in these discussions to evaluate both the presence and the origin of the oceanic crust, which can be preserved in a variety of ways (table 3).

(a) Stratigraphic continuity: If a stratigraphic unit can be continuously traced across the strike of an orogenic belt, the presence of younger ocean crust or subduction zones within the belt is ruled out (Cady, 1972). The presence of older ocean crust is not ruled out, even if identical basement rocks are exposed on opposite flanks of the belt or within the belt, because such basement rock relations could be attributed to rifting, development of marginal seas, or transcurrent faulting. Stratigraphic continuity of older rocks across orogenic belts is inevitably interrupted by synclinoria or by successor basins of younger clastic fill. This observation allows relatively free interpretation of the nature of basement and position of ancient subduction zones beneath such synclinoria.

Where allochthonous relations are dominant, vertical stratigraphic continuity is critical. In the Alpine nappes, the sedimentary and ophiolite sequences apparently show both allochthonous and autochthonous relations with each other and with pre-Triassic sialic basement (Lemoine, 1972). Hence, we may conclude that the nappes are stratigraphically both ensimatic and ensialic,

---

and some are en
turally ensialic.
(b) Initial se
sedimentary env
may be distinctiv
Afar Triangle
Red Sea may be
example of rifte
sediments here
water carbonates
as 3 km of evapo
complex mosaic
young volcanic b
but widespread
Engels, 1972).
central basin of
tinctive thermal
enriched pelagic
1969). Sialic ri
ocean basins or b
or aulacogens (t
Ocean basins
post-Alpine basi
probably spheno
form between
1971). Developm
carbonate facies
facies deposition
of sedimentary
(table 3) is likel
Typical deep-
cherts, and pelag
be encountered
oceanic crust, in
volcanoes, or c
(table 3). Proof
depths, however
The similarity
tonically emplace
lying the basalti
mined by deep-s
ocean-crust orig
The occurrence
in various tecto
including all va
table 3, but is no
elements.
The sedimenta
and interarc basi
tile to deep-wate
are not diagnost
may be found in
arcs. If the pyro
tary rocks are
topography is su
basement is not
(1972) have pr
submarine mafic

ts

1 for examples)

plock faulting; prisms of
ritus; peralkaline basalts
ectly coupled to zone of
ne fans and turbidites;

ılts; block faulting; sub-

: oozes, cherts
.tes and tuffs; both pyro-

translated sialic blocks;
nd restricted basin facies

anoes

Example
New Caledonia Franciscan
Indus suture Western Cordillera of Colombian Andes? Central Newfoundland Appalachians Alpine belt

be preserved in a vari-

ntinuity: If a strati-
:inuously traced across
c belt, the presence of
ubduction zones within
ly, 1972). The presence
not ruled out, even if
are exposed on oppo-
ər within the belt, be-
k relations could be at-
·elopment of marginal
ting. Stratigraphic con-
.cross orogenic belts is
synclinoria or by suc-
clastic fill. This obser-
free interpretation of
and position of ancient
h such synclinoria.
relations are dominant,
ɔntinuity is critical. In
dimentary and ophiolite
ıow both allochthonous
ıtions with each other
ılic basement (Lemoine,
onclude that the nappes
ı ensimatic and ensialic,

and some are ensimatic detachments but structurally ensialic.

(b) Initial sedimentary environments: The sedimentary environments of rifts (table 3) may be distinctive. The East African Rift, the Afar Triangle of Ethiopia, and the adjacent Red Sea may be considered collectively as an example of rifted sialic crust. The distinctive sediments here are fluviatile clastics, shollow-water carbonates (including reefs) and as much as 3 km of evaporites. In the Afar Triangle, the complex mosaic of Precambrian crystalline and young volcanic blocks indicates crustal thinning but widespread sialic crust (Hutchinson and Engels, 1972). In contrast, the fully oceanic central basin of the Red Sea Rift displays distinctive thermal saline brines and heavy metal-enriched pelagic sediments (Degens and Ross, 1969). Sialic rifts may develop into normal ocean basins or become arrested to form grabens or aulacogens (table 3).

Ocean basins such as the post-Hercynian and post-Alpine basins of the Mediterranean are probably sphenochasms (Carey, 1958), which form between rotating sialic blocks (Smith, 1971). Development of deep-water clastic and carbonate facies follows probable initial rift-facies deposition (Hsü, 1972). The succession of sedimentary environments in rhombochasms (table 3) is likely similar.

Typical deep-sea sediments are turbidites, cherts, and pelagic oozes. Such sediments should be encountered in sequences overlying normal oceanic crust, including crust beneath oceanic volcanoes, or crust preserved in reentrants (table 3). Proof of deposition at true oceanic depths, however, is difficult (Hallam, 1967). The similarity of sediments overlying or tectonically emplaced with ophiolites to those overlying the basaltic layer of the ocean, as determined by deep-sea drilling, corroborates their ocean-crust origin (Glennie and others, 1973). The occurrence of flysch-type facies is possible in various tectonic settings (Reading, 1972), including all varieties of ocean crust given in table 3, but is not diagnostic of oceanic tectonic elements.

The sedimentary environments of oceanic arcs and interarc basins (table 3) accumulate fluviatile to deep-water volcanogenic sediments, which are not diagnostic of oceanic crust as they also may be found in cordilleran arcs or indetached arcs. If the pyroclastic and associated sedimentary rocks are largely submarine, low oceanic topography is suggested, although true oceanic basement is not proven. Walker and Croasdale (1972) have presented criteria for diagnosing submarine mafic pyroclastic activity.

(c) Composition of detritus: Kay (1951) first emphasized the significance of plutonic pebble conglomerates for eugeosynclinal development. The composition of detritus reflects source area. The sources of detrital quartz and K-feldspar within eugeosynclinal furrows may be cratons, microcontinental sialic blocks, oceanic arcs, cordilleran arcs, or deformed sedimentary ridges (producing recycled detritus). The acid plutonic detritus of oceanic arcs is characteristically tonalitic, rich in silica but low in potash (Helwig and Sarpi, 1969; Mitchell and Reading, 1971), and generally much less important than associated quartz-poor detritus of intermediate to mafic volcanic provenance. On the other extreme, microcontinental fragments predictably yield more abundant and more potassic detritus as well as metamorphic rock fragments and minerals (de Booy, 1966). Cordilleran arcs yield detritus compositionally intermediate between ocean arcs and microcontinents, depending on the degree of unroofing of the basement.

Crook (this volume) and Dickinson (1970) have summarized the genetic significance of these compositional contrasts. The detritus provides substantial evidence of the nature and proximity of uplifted tectonic elements. The basement of the trough receiving the detritus may be evaluated in terms of its paleotectonic relationship to the source area (fig. 2).

Ophiolites also can be emergent, as on Cyprus, and shed mafic and ultramafic detritus. This is well known in Cuba and New Caledonia and was more recently described from Newfoundland (Church, 1969) and the western cordillera of North America (Monger, Souther, and Gabrielse, 1972; Churkin, this volume). If the source block shows continuous subsequent linkage with the depositional block, the source block contains ensimatic tectonic elements, although consideration must be given to the possibility that the source block is inevitably displaced and also may be allochthonous (obducted) (see fig. 2 d, f).

(d) Igneous rock geochemistry: Compositional gradients are observed in igneous rocks where detailed sampling profiles have been made across island arcs (Kuno, 1959; Hatherton and Dickinson, 1967), major young plutonic belts (Moore, 1959), and batholiths (Bateman and Dodge, 1970). The most notable gradient is an increase in potassium and potassium-type elements (Rb, Ba, Sr) at constant silica level from the volcanic front of the arc toward its foreland. The gradient occurs in rocks of basaltic to andesitic composition, both plutonic and volcanic. This geochemical gradient, when first observed in Pacific arcs, was correlated with

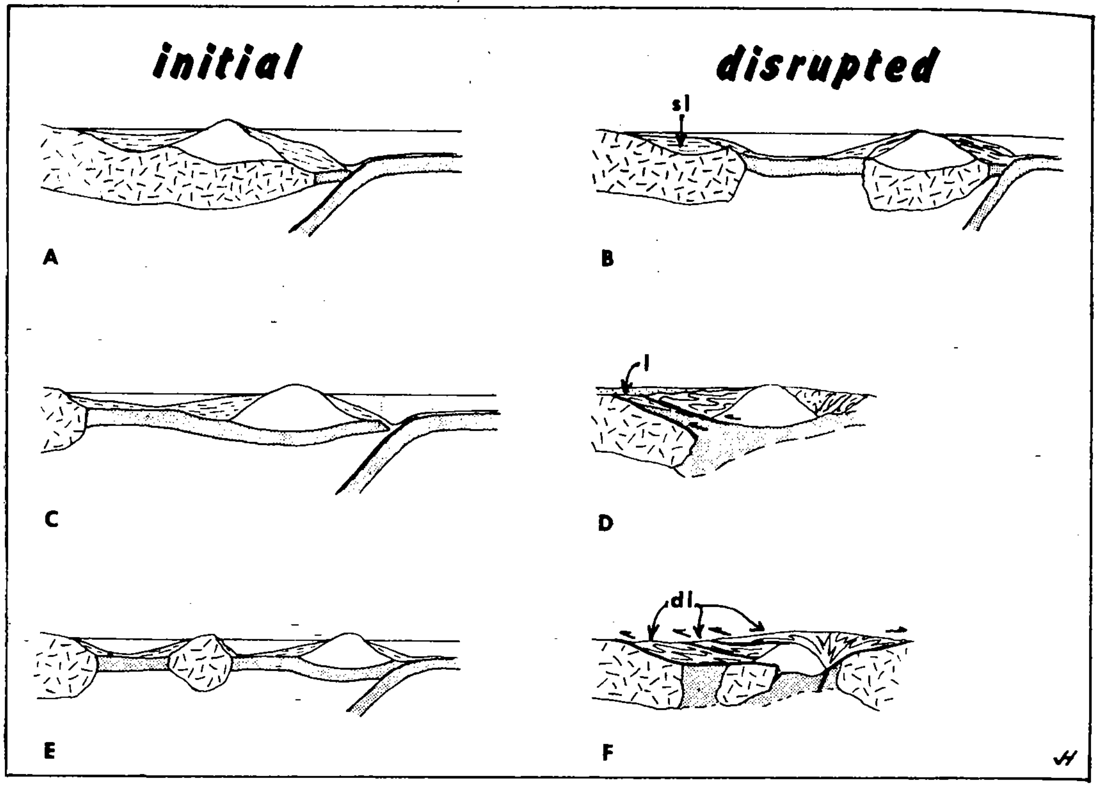


FIG. 2.—Some possible relations of sediment-source linkages. (Symbols: shaded, oceanic crust; random dashes, continental crust; dashed, sediments; open, arcs and sea water). Diagrams on left show initial configurations; on right, disrupted situations. A, Cordilleran arc and flanking ensialic pericratonic and arc-trench geosynclines. B, Same as A after opening of marginal basin; separated linkage (sl) exists between sediments of pericratonic geosyncline and source in detached arc. C, Oceanic arc and flanking ensimatic sediment wedges. D, Same as C after closing of marginal basin; linkage (L) of cratonic margin sediments from oceanic arc and microcontinent source areas. E, Small ocean basins receiving sediments from oceanic arc and microcontinent source areas. F, Same as E after suturing by continental collision; disjunctive linkages (dl) of thrust sheets indicates disordering and covering of originally linked source areas.

depth of melting in the mantle as related to the inclined seismic zones or arcs (Kuno, 1966; Hatherton and Dickinson, 1967). Such geochemical gradients, however, now appear to occur in time as well as space (Jakes and White, 1972) and thus could reflect crustal thickness and composition (Condie and Potts, 1970). If this interpretation is correct, we then have a means of evaluating eugeosynclinal basement.

Data on abundances of major elements, trace elements, and Sr isotopes justify the view that basement types can be inferred chemically (table 4). The compositional data for volcanic rocks allow distinction of three important basement types: generative ocean crust (abyssal tholeiites), ocean arc crust (distinctive arc thoeliites and calc-alkaline suite), and continental crust of cordilleran arcs (calc-alkaline and silicic rocks). [Detached arcs having continental crust as basement (Japan type), and ensialic volcanic provinces of the Basin and Range-type do not appear to be geochemically distinctive at present.] Undoubtedly this approach will prove applicable to plutonic rocks as well, but at present sufficient data are not widely available.

The underlying cause of these compositional distinctions involves the origin of magmas, a problem not without opposing views (Boettcher, 1973). Controversy centers about the relative contributions of oceanic crust, upper mantle, oceanic sediments, and continental crust to the various magmas. From this viewpoint it appears that the three types of magmatic evolution summarized in table 4 involve three different sources that are nevertheless interrelated. The abyssal tholeiites are the direct products of partial melting of the upper mantle at midocean ridges. The arc tholeiites form by partial melting and de-

---

hydration of abyssa
descending lithosph
(Fitton, 1971; Wy
of arc tholeiites fro
explained, whereas
to contamination by
ing ascent of the
Christie, 1971). Th
of ocean arcs conta
nitic rocks because
apparently are rem
mantle rocks becon
fractions. The C
series may be cor
lower crustal rocks
ferentiated as is a
upper crustal rock
Andean-type arcs,
ignimbrites contair
0.710 (Pushkar, M
Such ignimbrites a
areas of pre-Meso
ment rocks such as
Central America, a
formation and thic
apparently involves
tial melting of ma
partial remelting o
sequences and, ev
tion, by remelting
typically continenta
broic, but partly g
1972).

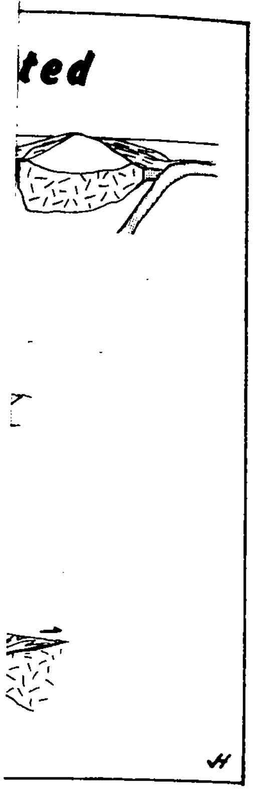
The data and ir
that igneous rock g

TAB

Parameter
Existing crust, that is, inherited basement
SiO_2 (%)
K_2O (%)
K_2O/Na_2O
Al_2O_3 (%)
Fe enrichment
Rare earth elements
K/Rb
Rb, Ba, Sr (ppm)
Th, U, Zr (ppm)
Sr^{87}/Sr^{86}

---

[1] Data generalize
Peterman and Hedge



, oceanic crust; random
:ft show initial configura-
:onic and arc-trench geo-
.sts between sediments of
ıatic sediment wedges. D,
nts from oceanic arc and
c arc and microcontinent
ges (dl) of thrust sheets

ı, and ensialic volcanic
.nd Range-type do not
lly distinctive at pres-
ɔproach will prove ap-
as well, but at present
dely available.
of these compositional
origin of magmas, a
sing views (Boettcher,
ers about the relative
crust, upper mantle,
ontinental crust to the
ıis viewpoint it appears
agmatic evolution sum-
: three different sources
:errelated. The abyssal
roducts of partial melt-
.t midocean ridges. The
artial melting and de-

hydration of abyssal tholeiites at the top of the descending lithosphere slab below island arcs (Fitton, 1971; Wyllie, 1973). The differences of arc tholeiites from abyssal tholeiites are thus explained, whereas the similarities may be due to contamination by upper mantle material during ascent of the magma (White, Jakes, and Christie, 1971). The upper stratigraphic levels of ocean arcs contain calc-alkaline and shoshonitic rocks because with time, basal arc tholeiites apparently are remelted coincident with upper mantle rocks becoming depleted of low-melting fractions. The Cordilleran-type calc-alkaline series may be contaminated by remelting of lower crustal rocks, which are at least as differentiated as is a mature oceanic arc. Even upper crustal rocks may be remelted in such Andean-type arcs, producing young rhyolitic ignimbrites containing Sr^{87}/Sr^{86} in excess of 0.710 (Pushkar, McBirney and Kudo, 1972). Such ignimbrites are only known to occur in areas of pre-Mesozoic crystalline sialic basement rocks such as in the western United States, Central America, and the Andes. In summary, formation and thickening of continental crust apparently involves magma generation by partial melting of mantle, followed by increasing partial remelting or cannabilization of basaltic sequences and, eventually, through superposition, by remelting of previously consolidated typically continental lower crust of mostly gabbroic, but partly granitic composition (Glikson, 1972).

The data and interpretations above indicate that igneous rock geochemistry may provide the best evidence for direct comparison of modern and ancient tectonic elements located above subduction zones. The spatial variation of igneous rocks can be related in part to depth to a subduction zone (Dickinson, 1970). The stratigraphic succession and composition of igneous rocks can be related to basement type (table 4). The study of trace elements may circumvent compositional modifications produced by metamorphism (Pearce and Cann, 1971).

As yet, few systematic regional studies of igneous rocks in pre-Mesozoic orogenic belts have been done that are sufficiently detailed to allow definition of subduction zones or of basement types. (However, see the many studies of Archaean greenstones, which suggest ocean-arc origin, or the study by Fitton and Hughes, 1970, suggesting a southeast-dipping subduction zone beneath the early Paleozoic Welsh geosyncline-marginal basin). Assuming metamorphism plays a negligible role in compositional zoning of crust, data presently available show that arc tholeiites are major components of Archaean greenstones and that ensimatic tectonic elements probably were widespread in ancient eugeosynclines.

(e) Geophysics: Gravity and seismic data show that active consuming plate margins contain every transition between continental and oceanic crust. In ancient crushed orogenic belts, interpreting such geophysical data in terms of continental and oceanic crust is nearly impossible because of the inherently altered character and complexity of tectonic elements; longitudinal, rather than across-strike geophysical sur-

TABLE 4.—OROGENIC VOLCANIC GEOCHEMISTRY RELATED TO BASEMENT TYPE[1]

Parameter	Abyssal tholeiite	Oceanic arc		Cordilleran Arc (Andean)
Existing crust, that is, inherited basement	None: generative setting of ophiolite	Ocean crust (ensimatic) plus arc tholeiites		Continental crust (ensialic)
SiO_2 (%)	<50	50–66		56–75 (including silicic ignimbrites)
		Arc tholeiites	Calc-alkaline	Calc-alkaline
K_2O (%)	<0.3	0.3–0.5	1.0–2.7	1.1–3.4
K_2O/Na_2O	<0.1	<0.5	<0.8	0.6–1.1
Al_2O_3 (%)	12–18	14–18	15–19	15.2–18.2
Fe enrichment	High	Moderate	Low	None
Rare earth elements	Chondritic	Chondritic	Light rare earth elements enriched	—
K/Rb	1000	1000	400	230
Rb, Ba, Sr (ppm)	2, 30, 120	5, 100, 200	30, 270, 385	80, 680, 700
Th, U, Zr (ppm)	—	0.5, 0.3, 70	2.2, 0.7, 110	—, —, 210
Sr^{87}/Sr^{86}	0.701–0.702	0.703–0.706	0.703–0.706	0.704–0.707

[1] Data generalized from: Ewart and Bryan, 1972; Jakes and White, 1972; Kay, Hubbard, and Gast, 1970; Peterman and Hedge, 1971; Pichler and Zeil, 1972; Pushkar, 1968; and White, Jakes, and Christie, 1971.

veys within tectonic elements, however, possibly can delineate to some extent the crustal contrasts between adjacent elements. That steep gravity gradients are characteristic of contrasts between oceanic and continental tectonic elements (Case and others, 1971) is noteworthy.

The most useful application of geophysics has been to the study of marginal basins (Packham and Falvey, 1971), reentrant small ocean basins, sphenochasms, and rhombochasms inasmuch as these features may be altered only by having great sediment cover (Fedynsky and others, 1972). Studies of the Black Sea and the Gulf of Mexico show that negative gravity anomaly, weak magnetic relief, and deep thin gabbroic crust are characteristic of such remnant ensimatic basins so long as they have not undergone significant deformation or magmatism. Remnant ocean basins may have an arc on their plate, which could make them similar to marginal basins. However, marginal basins characteristically have positive gravity anomalies (Packham and Falvey, 1971).

(f) Diatreme sampling: Late orogenic or postorogenic igneous rocks, particularly in diatremes, may bring xenoliths of basement and even mantle rocks to the surface. There has been little effort to analyze such samples, but that would seem to be well worth the effort inasmuch as the nature and age of both crust and mantle beneath orogens conceivably could be determined. Two examples of this approach are: (1) presence of gneiss, amphibolite, and grandodiorite xenoliths in volcanic rocks of the Aeolian Islands show the existence of sialic basement (Honnorez and Keller, 1968) and (2) presence of ultramafic inclusions in intrusions cutting the Dunnage Mélange of Newfoundland (Kay, 1972) suggest the presence of an ophiolitic basement.

CONCLUSIONS

The addition of oceanic and mantle materials to the continent by accretion of orogens, an irreversible process, is complex due to the interaction and evolution of tectonic elements affected by complex tectonic processes. The portions of eugeosynclinal belts that are ensimatic may be delineated by several approaches, none of which is adequately demonstrated as being definitive for both young and ancient examples. These approaches attempt to relate the rock compositions of tectonic elements to their basement types. Taken together, available data of this type suggest that ophiolitic elements and a considerable portion of the arcs and furrows of eugeosynclines are probably ensimatic. The actual processes that generate tectonic elements are not understood, but clearly the mutual interrelations of elements during orogenesis strongly reflect basement type. Thus, basement exerts a key role in orogenesis.

The sialic vs. simatic nature and extent of the inherited and generative basement of eugeosynclinal belts is highly varied and dependent upon the evolution of the individual orogen in terms of the starting configuration of rifts, trenches, transform faults, arcs and marginal basins, and reentrants and in terms of their subsequent termination as new configurations evolve. Tectonic processes that continue in a stable configuration generally lead to an orderly array of tectonic elements. But the establishment of new configurations by displacements and the ultimate suturing and crushing of major orogenic zones may produce a disordering of tectonic elements. Thus, single tectonic processes or tectonic elements may be described but not single theories, cycles, or finite models of orogenesis (Coney, 1970). Each orogen is a unique time-space collage of tectonic elements.

The objection may be raised that a collage "model" (a misnomer) of orogenesis is scientific anarchy, telling us that each mountain belt has its own absolutely unique history and that no general theory of orogenesis is possible. This objection cannot be sustained in a historical science like geology for two reasons. First, the collage concept is not a model in conflict with either plate models or orogenic theories but is a word picture that attempts to convey the idea that various models and theories can be integrated and reconciled to yield insight into the astonishing complexities, similarities, and differences of mountain belts. The so-called odd rocks of mountain belts (Fischer, this volume) are not really odd; they simply show that every type of crustal rock (and some mantle rocks) can be exposed in eugeosynclines. Any orogenic paradigm apparently cannot involve limitations on the kind of rock that occurs in orogens. Second, just as the theory of evolution provides a simple explanation for the diversity of life, it also explains why no species of plant or animal ever arose twice. By analogy, a collage conception of orogenesis offers a simple explanation for the diversity of orogens, and it also explains why no two crustal configurations are ever exactly the same—a truism to which we would all admit (Trümpy, 1971, p. 294).

The fact that there may be a limited number of tectonic elements (table 1), particularly in the beginning stages of accreting and consuming plate margins (Dewey and Bird, 1970), does suggest that the initial stages of development of orogenic belts can be represented by a limited

number of models
of a midplate con
plate margin prod
geocline to eugeo
ever, as orogenic
elements are link
ments governed t
conposition, and
modified by segm
faulting, and supe
and are affected
coupling and dec
extension. All the
repeated in prec
addition or subtra
mountain belts es
nesis is noncomm

The evolution
ferent. Plate tect
that allow unders
tion of an oroger
represent method
tive uniformitar
models should nc
quately anything
stage of develo
orogen. Thus, th
tonic element m
analogy with spe
(table 1). There
orogen requires
models, and it is
by considering th
plate model. The
ing, of tectonic

AUBOUIN, F., 196
335 p.
BATEMAN, P. C.,
Sierra Nevada
BEMMELEN, R. S
Genoot. Verh.
BIRD, J. M., AND
Appalachian C
BOETTCHER, A. L.
240.
BOGDANOV, N. A.,
BOOY, T. DE, 1967
menten der Te
BORUKAYEV, C. B
BOTT, M. H. P., 1
v. 11, p. 319–3
CADY, W. M., 19
logous?: Jour
CAREY, S. W., 19
Tasmania, Ur
CASE, J. E., AND
America Bull
CHIDESTER, A. H.
Phys. Sci., v.
CHURCH, W. R.,

learly the mutual in-
during orogenesis
type. Thus, basement
nesis.
ture and extent of the
asement of eugeosyn-
d and dependent upon
idual orogen in terms
ion of rifts, trenches,
marginal basins, and
of their subsequent
urations evolve. Tec-
nue in a stable con-
to an orderly array
the establishment of
isplacements and the
shing of major oro-
a disordering of tec-
gle tectonic processes
be described but not
finite models of oro-
ch orogen is a unique
nic elements.
raised that a collage
f orogenesis is scien-
at each mountain belt
ique history and that
nesis is possible. This
ned in a historical sci-
o reasons. First, the
nodel in conflict with
genic theories but is a
ts to convey the idea
theories can be inte-
yield insight into the
similarities, and dif-
ts. The so-called odd
Fischer, this volume)
imply show that every
l some mantle rocks)
nclines. Any orogenic
ot involve limitations
t occurs in orogens.
of evolution provides
he diversity of life, it
ies of plant or animal
ogy, a collage concep-
a simple explanation
s, and it also explains
urations are ever ex-
to which we would all
294).
y be a limited number
le 1), particularly in
ccreting and consum-
and Bird, 1970), does
ges of development of
resented by a limited

number of models. For example, the conversion of a midplate continental margin to consuming plate margin produces the transition from miogeocline to eugeosyncline-exogeosyncline. However, as orogenic evolution proceeds, tectonic elements are linked or separated by displacements governed by boundary geometry, crustal conposition, and plate motions. Elements are modified by segmentation, changes of boundary faulting, and superposition of tectonic processes, and are affected by one or more episodes of coupling and decoupling and compression and extension. All these processes would have to be repeated in precisely the same order without addition or subtraction in order to produce two mountain belts essentially alike (fig. 1). Orogenesis is noncommutative.

The evolution of each orogen is thereby different. Plate tectonic models are process models, that allow understanding of each step in evolution of an orogen, just as all models in geology represent methodological, rather than substantive uniformitarianism (Gould, 1965). Plate models should not be construed to portray adequately anything other than a generalized single stage of development of part of a specific orogen. Thus, the understanding of each tectonic element may be gained most readily by analogy with specific modern tectonic elements (table 1). Therefore, understanding an entire orogen requires superposition of many plate models, and it is doubtful that much is learned by considering that an entire orogen fits a single plate model. The assembling, including disordering, of tectonic elements can be understood by returning the pieces of the collage to "tectonically reasonable positions, revealing major igneous, metamorphic and deformational belts" (Gastil and others, 1972) for specific times in the past. The task of understanding orogenic belts thus assumes the broadest conceivable palinspastic problems, which are not easily solved (Monger, Souther, and Gabrielse, 1972; Schenk, 1972). In making palinspastic reconstructions, geologic fits of all kinds may be especially strengthened if geologic *gradients* can be reconstructed (Whitten, 1969), as Ross (1973) has attempted for the compositional gradients in the granitic rocks of the Sierra Nevada and Salinian block in California.

The remaining fundamental question now appears to be directed to what controls the sequence of processes in plates and orogenic belts, not what are the models of orogens (Khain, 1972). Do plate boundaries and orogenic collages follow any particular rules, so to speak, of migration and assemblage respectively that we may observe in the crustal records? Have these process rules changed through geologic time? How are the similarities of orogens (Dott, 1964) explained? What about processes and rules of orogenesis that are overlooked by present emphasis on plate boundaries and plate models (Gilluly, 1972; Ramberg, 1972)? It seems probable to me that some quantifiable rules are followed in which energy is dissipated (Griggs, 1972) with maximum efficiency and minimum work, following a pathway toward continentalization.

REFERENCES

AUBOUIN, F., 1965, Geosynclines: developments in geotectonics: Amsterdam, Elsevier Publishing Co., v. 1, 335 p.

BATEMAN, P. C., AND DODGE, F. C. W., 1970, Variations of major chemical constituents across the central Sierra Nevada Batholith: Geol. Soc. America Bull., v. 81, p. 409–420.

BEMMELEN, R. S. VAN, 1969, Origin of the western Mediterranean Sea: K. Nederlandsch Geol. Mijnb. Genoot. Verh., v. 26, p. 13–52.

BIRD, J. M., AND DEWEY, J. F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian Orogen: Geol. Soc. America Bull., v. 81, p. 1031–1059.

BOETTCHER, A. L., 1973, Volcanism and orogenic belts-the origin of andesites: Tectonophysics, v. 17, p. 223–240.

BOGDANOV, N. A., 1969, Thalassogeosynclines of the Circumpacific ring: Geotectonics, 1969, p. 141–147.

BOOY, T. DE, 1967, Nue Daten fur die Annahme einer sialischen Kruste unter den fruhgeosynklinalen Sedimenten der Tethys: Geol. Rundschau, v. 56, p. 94–102.

BORUKAYEV, C. B., 1970, Palinspastic representations: Geotectonics, 1970, p. 343–346.

BOTT, M. H. P., 1971, Evolution of young continental margins and formation of shelf basins: Tectonophysics, v. 11, p. 319–327.

CADY, W. M., 1972, Are the Ordovician northern Appalachians and the Mesozoic Cordilleran system homologous?: Jour. Geophys. Research, v. 77, p. 3806–3815.

CAREY, S. W., 1958, The tectonic approach to continental drift, *in* Continental drift—a symposium: Hobart, Tasmania, Univ. Hobart, p. 177–355.

CASE, J. E., AND OTHERS, 1971, Tectonic investigations in western Colombia and eastern Panama: Geol. Soc. America Bull., v. 82, p. 2685–2712.

CHIDESTER, A. H., AND CADY, W. M., 1972, Origin and emplacement of Alpine-type ultramafic rocks: Nature Phys. Sci., v. 240, no. 98, p. 27–31.

CHURCH, W. R., 1969, Metamorphic rocks of Burlington Peninsula and adjoining areas of Newfoundland,

and their bearing on continental drift in North Atlantic, *in* Kay, M. (ed.), North Atlantic—Geology and continental drift: Am. Assoc. Petroleum Geologists Mem. 12, p. 212–235.

Coleman, R. G., 1971, Plate tectonic emplacement of upper mantle peridotites along continental edges: Jour. Geophys. Research, v. 76, p. 1212–1222.

Condie, K. C., and Potts, M. J., 1969, Calc-alkaline volcanism and the thickness of the early Precambrian crust in North America: Canadian Jour. Earth Sci., v. 6, p. 1179–1184.

Coney, P. J., 1970, The geotectonic cycle and the new global tectonics: Geol. Soc. America Bull., v. 81, p. 739–748.

Degens, E. T., and Ross, D. A. (eds.), 1969, Hot brines and recent heavy metal deposits in the Red Sea: New York, Springer Verlag, 600 p.

Dewey, J. F., 1969, Continental margins: a model for conversion of Atlantic type to Andean type: Earth and Planetary Sci. Letters, v. 6, p. 189–197.

———, and Bird, J. M., 1970, Mountain belts and the new global tectonics: Jour. Geophys. Research, v. 75, p. 2625–2647.

———, and ———, 1971, Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland: *ibid.*, v. 76, p. 3179–3206.

Dickinson, W. R., 1970, Relations of andesites, granites, and derivative sandstones to arc-trench tectonics: Rev. Geophysics and Space Physics, v. 8, p. 813–860.

———, 1971, Plate tectonic models of geosynclines: Earth and Planetary Sci. Letters, v. 10, p. 165–174.

Dietz, R., 1963, Collapsing continental rises: an actualistic concept of geosynclines and mountain building: Jour. Geology, v. 71, p. 314–333.

Dott, R. H., Jr., 1964, Superimposed rhythmic stratigraphic patterns in mobile belts: Kansas Geol. Survey Bull. 169, p. 69–85.

Drake, C. L., Ewing, M., and Sutton, G. H., 1959, Continental margins and geosynclines: the east coast of North America north of Cape Hatteras, *in* Physics and chemistry of the earth: London, Pergamon Press, v. 3, p. 110–198.

Ernst, W. G., 1973, Interpretative synthesis of metamorphism in the Alps: Geol. Soc. America Bull., v. 84, p. 2053–2078.

Ewart, A., and Bryan, W. B., 1972, Petrography and geochemistry of the igneous rocks from Eua, Tongan Islands: *ibid.*, v. 83, p. 3281–3298.

Fedynsky, V. V., and others, 1972, The earth's crust of the inland seas and continental depressions of the west Tethys region: 24th Intnat. Geol. Cong., Sec. 3, p. 51–57.

Fitton, J. G., 1971, The generation of magmas in island arcs: Earth and Planetary Sci. Letters, v. 11, p. 63–67.

———, and Hughes, D. J., 1970, Volcanism and plate tectonics in the British Ordovician: *ibid.*, v. 8, p. 223–228.

Fyfe, W. S., 1973, The generation of batholiths: Tectonophysics, v. 17, p. 273–283.

Gansser, A., 1966, The Indian Ocean and the Himalaya: Eclogae Geol. Helvetiae, v. 59, p. 831–848.

———, 1973, Facts and theories on the Andes: Geol. Soc. London Quart. Jour., v. 129, p. 93–131.

Gastil, G., Phillips, R. P., and Rodriguez-Torres, R., 1972, The reconstruction of Mesozoic California: 24th Intnat. Geol. Cong., Sec. 3, p. 217–229.

Gilluly, J., 1972, Tectonics involved in the evolution of mountain ranges, *in* Robertson, E. C. (ed.), The nature of the solid earth: New York, McGraw-Hill Book Co., p. 414–447.

Glennie, K. W., and others, 1973, Late Cretaceous nappes in Oman Mountains and their geologic evolution: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 5–27.

Glikson, A. Y., 1972, Early Precambrian evidence of a primitive ocean crust and island nuclei of sodic granite: Geol. Soc. America Bull., v. 83, p. 3323–3344.

Gould, S. J., 1965, Is uniformitarianism necessary?: Am. Jour. Sci., v. 263, p. 223–228.

Griggs, D. T., 1972, The sinking lithosphere and the focal mechanism of deep earthquakes, *in* Robertson, E. C. (ed.), The nature of the solid earth: New York, McGraw-Hill Book Co., p. 361–384.

Hall, James, 1859, Description and figures of the organic remains of the lower Helderberg Group and the Oriskany Sandstone: New York Geol. Survey, National History of New York, pt. 6, Paleontology, v. 3, 532 p.

Hallam, A. (ed.), 1967, Depth indicators in marine sedimentary environments: Marine Geology, v. 5, no. 5, 6, 240 p.

Hamilton, W., 1969, Mesozoic California and the underflow of Pacific mantle: Geol. Soc. America Bull., v. 80, p. 2409–2430.

Harland, W. B., 1971, Tectonic transpression in Caledonian Spitsbergen: Geol. Mag., v. 108, p. 27–41.

Hatherton, T., and Dickinson, W. R., 1967, Andesitic volcanism and seismicity around the Pacific: Science, v. 157, p. 801–803.

Haug, E., 1900, Les géosynclinaux et les aires continentales: Soc. géol. France Bull., v. 28, p. 617–711.

Helwig, J., 1972, Stratigraphy, sedimentation, paleogeography, and paleoclimates of Carboniferous ("Gondwana") and Permian of Bolivia: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 1008–1033.

———, 1973, Plate tectonic model for the evolution of the central Andes: discussion: Geol. Soc. America Bull., v. 84, p. 1493–1496.

———, and Sarpi, E., 1969, Plutonic-pebble conglomerates, New World Island, Newfoundland, and history of eugeosynclines, *in* Kay, M. (ed.), North Atlantic—Geology and continental drift: Am. Assoc. Petroleum Geologists Mem. 12, p. 443–466.

Hess, H. H., 1962, History of ocean basins, *in* Engle, A. E. J., James, H. L., and Leonard, B. L. (eds.), Petrologic studies: a volume in honor of A. F. Buddington: Boulder, Colorado, Geol. Soc. America, p. 599–620.

Honnorez, J., and
Geol. Rundscha
Hsü, K. J., 1972,
Hutchinson, R.
significance to
Isacks, B. I., Oliv
Research, v. 73,
Jakes, P., and W
areas: Geol. So
Karig, D. E., 1971,
v. 76, p. 2542–25
Kay, M., 1944, Ge
———, 1951, North
———, 1972, Dunn
Geol. Cong., Se
———, and Craw
thrust slices, c
Kay, R., Hubbar
volcanic rocks:
Khain, V. Ye., 1
p. 199–214.
King, P. B., 1969,
America, scale
Kober, L., 1928, De
Kuno, H., 1966, L
W. H. (ed.),
Lemoine, M., 1972
Geol. Cong., Se
Le Pichon, X., 19
McKenzie, D. P.,
McGraw-Hill
Matsuda, T., and
concept and p
Mitchell, A. H.,
Jour. Geology,
———, 1971, Evolu
Monger, J. W. H.,
tectonic model
Moore, J. G., 195
p. 198–210.
Mouratov, M., 19
Intnat. Geol. C
Oxburgh, E. R.,
Packham, G. H.,
Pacific: Tecto
Pearce, J. A., an
Y: Earth and
Peterman, Z. E.,
basalts: Geol.
Peyve, A. V., 1967,
———, 1969, Ocea
———, Perfiliev,
Intnat. Geol. C
Pichler, H., and
Volcanol., v. 3
Plafker, G., 1972,
Jour. Geophys.
Pushkar, P., 196
2714.
———, McBirne
ignimbrites: E
Ramberg, H., 197
Research, v. 7
Reading, H. G., 1
p. 59–65.
Rodgers, J. 1968,
in Zen, E-An
maritime: Ne
Ross, D. C., 1973,
search, v. 1, p.

Atlantic—Geology and
ntinental edges: Jour.
he early Precambrian
.America Bull., v. 81,
osits in the Red Sea:
ndean type: Earth and
phys. Research, v. 75,
an ophiolites in New-
arc-trench tectonics:
v. 10, p. 165–174.
nd mountain building:
: Kansas Geol. Survey
nclines: the east coast
h: London, Pergamon
. America Bull., v. 84,
cks from Eua, Tongan
ntal depressions of the
Letters, v. 11, p. 63–67.
cian: *ibid.*, v. 8, p. 223–
59, p. 831–848.
p. 93–131.
f Mesozoic California:
rson, E. C. (ed.), The
heir geologic evolution:
island nuclei of sodic
hquakes, *in* Robertson,
361–384.
lderberg Group and the
rk, pt. 6, Paleontology,
Marine Geology, v. 5,
ol. Soc. America Bull.,
., v. 108, p. 27–41.
round the Pacific: Sci-
., v. 28, p. 617–711.
Carboniferous ("Gon-
, p. 1008–1033.
on: Geol. Soc. America
wfoundland, and history
tal drift: Am. Assoc.
Leonard, B. L. (eds.),
do, Geol. Soc. America,

Honnorez, J., and Keller, J., 1968, Xenolithen in vulkanischen Gesteinen der Äolischen Inseln (Sizilien): Geol. Rundschau, v. 57, p. 719–736.

Hsü, K. J., 1972, Alpine flysch in a Mediterranean setting: 24th Intnat. Geol. Cong., Sec. 6, p. 67–74.

Hutchinson, R. W., and Engels, G. G., 1972, Tectonic evolution in the southern Red Sea and its possible significance to older rifted continental margins: Geol. Soc. America Bull., v. 83, p. 2987–3002.

Isacks, B. I., Oliver, J., and Sykes, L. R., 1968, Seismology and the new global tectonics: Jour. Geophys. Research, v. 73, p. 5855–5899.

Jakes, P., and White, A. J. R., 1972, Major and trace element abundances in volcanic rocks of orogenic areas: Geol. Soc. America Bull., v. 83, p. 29–40.

Karig, D. E., 1971, Origin and development of marginal basins in the western Pacific: Jour. Geophys. Research, v. 76, p. 2542–2561.

Kay, M., 1944, Geosynclines in continental development: Science, v. 99, p. 461–462.

———, 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

———, 1972, Dunnage Mélange and lower Paleozoic deformation in northeastern Newfoundland: 24th Intnat. Geol. Cong., Sec. 3, p. 122–133.

———, and Crawford, J. P., 1964, Paleozoic facies from the miogeosynclinal to the eugeosynclinal belt in thrust slices, central Nevada: Geol. Soc. America Bull., v. 75, p. 425–454.

Kay, R., Hubbard, N. J., and Gast, P. W., 1970, Chemical characteristics and origin of oceanic ridge volcanic rocks: Jour. Geophys. Research, v. 75, p. 1585–1613.

Khain, V. Ye., 1972, Present status of theoretical geotectonics and related problems: Geotectonics, 1972, p. 199–214.

King, P. B., 1969, The tectonics of North America—a discussion to accompany the tectonic map of North America, scale 1:5,000,000: U.S. Geol. Survey Prof. Paper 628, 94 p.

Kober, L., 1928, Der Bau der Erde: Berlin, Borntraeger, 500 p.

Kuno, H., 1966, Lateral variation of basaltic magma across continental margins and island arcs, *in* Poole, W. H. (ed.), Continental margins and island arcs: Geol. Survey Canada Paper 66–15, p. 317–336.

Lemoine, M., 1972, Eugeosynclinal domains of the Alps and the problem of past oceanic areas: 24th Intnat. Geol. Cong., Sec. 3, p. 476–485.

Le Pichon, X., 1968, Sea-floor spreading and continental drift: Jour. Geophys. Research, v. 73, p. 3661–3697.

McKenzie, D. P., 1972, Plate tectonics, *in* Robertson, E. C. (ed.), The nature of the solid earth: New York, McGraw-Hill Book Co., p. 323–360.

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

Mitchell, A. H., and Reading, H. G., 1969, Continental margins, geosynclines, and ocean floor spreading: Jour. Geology, v. 77, p. 629–646.

———, 1971, Evolution of island arcs: *ibid.*, v. 79, p. 253–284.

Monger, J. W. H., Souther, J. G., and Gabrielse, H., 1972, Evolution of the Canadian Cordillera: A plate-tectonic model: Am. Jour. Sci., v. 272, p. 577–602.

Moore, J. G., 1959, The quartz diorite boundary line in the western United States: Jour. Geology, v. 67, p. 198–210.

Mouratov, M., 1972, Main structural features of the crust on continents, their interrelations and age: 24th Intnat. Geol. Cong., Sec. 3, p. 71–78.

Oxburgh, E. R., 1972, Flake tectonics and continental collision: Nature, v. 239, p. 202–204.

Packham, G. H., and Falvey, D. A., 1971, An hypothesis for the formation of marginal seas in the western Pacific: Tectonophysics, v. 11, p. 79–109.

Pearce, J. A., and Cann, J. R., 1971, Ophiolite origin investigated by discriminant analysis using Ti, Zr and Y: Earth and Planetary Sci. Letters, v. 12, p. 339–349.

Peterman, Z. E., and Hedge, C. E., 1971, Related strontium isotopic and chemical variations in oceanic basalts: Geol. Soc. America Bull., v. 82, p. 493–500.

Peyve, A. V., 1967, Faults and tectonic movements: Geotectonics, v. 5, p. 268–275.

———, 1969, Oceanic crust of the geologic past: *ibid.*, 1969, p. 210–224.

———, Perfiliev, A. S., and Ruzhentsev, S. V., 1972, Problems of intracontinental geosynclines: 24th Intnat. Geol. Cong., Sec. 3, p. 486–493.

Pichler, H., and Zeil, W., 1972, The Cenozoic rhyolite-andesite association of the Chilean Andes: Bull. Volcanol., v. 35, p. 424–452.

Plafker, G., 1972, Alaskan earthquake of 1964 and Chilean earthquake of 1960: implications for arc tectonics: Jour. Geophys. Research, v. 77, p. 901–925.

Pushkar, P., 1968, Strontium isotope ratios in volcanic rocks of three island arc areas: *ibid.*, v. 73, p. 2701–2714.

———, McBirney, A. R., and Kudo, A. M., 1972, The isotopic composition of strontium in Central American ignimbrites: Bull. Volcanol., v. 35, p. 265–294.

Ramberg, H., 1972, Theoretical models of density stratification and diapirism in the earth: Jour. Geophys. Research, v. 77, p. 877–889.

Reading, H. G., 1972, Global tectonics and the genesis of flysch successions: 24th Intnat. Geol. Cong., Sec. 6, p. 59–65.

Rodgers, J. 1968, The eastern edge of the North American continent during the Cambrian and Early Ordovician, *in* Zen, E-An., White, W. S., and Hadley, J. B. (eds.), Studies of Appalachian geology: northern and maritime: New York, Interscience Publishers, p. 141–150.

Ross, D. C., 1973, Are the granitic rocks of the Salinian block trondhjemitic?: U.S. Geol. Survey Jour. Research, v. 1, p. 251–254.

SCHENK, P. E., 1972, Eastern Canada as successive remnants of northwestern Africa: 25th Internat. Geol. Cong., Sec. 6, p. 14–23.

SCLATER, J. G., ANDERSON, R. N., AND BELL, M. L., 1971, Elevation of ridges and evolution of the central Pacific: Jour. Geophys. Research, v. 76, p. 7888–7915.

SMITH, A. G., 1971, Alpine deformation and the oceanic areas of the Tethys, Mediterranean and Atlantic: Geol. Soc. America Bull., v. 82, p. 2039–2070.

STILLE, H., 1941, Einführung in den Bau Amerikas: Berlin, Borntraeger, 717 p.

THOMPSON, G. A., AND TALWANI, M., 1964, Geology of the crust and mantle, Western United States: Science, v. 146, p. 1539–1549.

TRÜMPY, R., 1960, Paleotectonic evolution of the central and Western Alps: Geol. Soc. America Bull., v. 71, p. 843–908.

———, 1971, Stratigraphy in mountain belts: Geol. Soc. London Quart. Jour., v. 126, p. 293–318.

VOGT, P. R., SCHNEIDER, E. D., AND JOHNSON, G. L., 1969, The crust and upper mantle beneath the sea, *in* HART, P. J. (ed.), The earth's crust and upper mantle: Am. Geophys. Union Geophys. Mon. 13, p. 556–617.

WALKER, G. P. C., AND CROASDALE, R., 1972, Characteristics of some basic pyroclastics: Bull. Volcanol., v. 35, p. 303–317.

WELLS, F. G., 1949, Ensimatic and ensialic geosynclines: Geol. Soc. America Bull., v. 60, p. 1927.

WHITE, A. J. R., JAKES, P., AND CHRISTIE, D. M., 1971, Composition of greenstones and the hypothesis of sea-floor spreading in the Archaean: Geol. Soc. Australia Special Pub. 3, p. 47–56.

WHITE, D. A., AND OTHERS, 1970, Subduction: Geol. Soc. America Bull., v. 81, p. 3431–3432.

WHITTEN, E. H. T., 1969, Continental-drift models and correlation of geologic features across North Atlantic Ocean, *in* KAY, M. (ed.), North Atlantic—Geology and continental drift: Am. Assoc. Petroleum Geologists Mem. 12, p. 919–930.

WILSON, J. T., 1949, The origin of continents and Precambrian history: Royal Soc. Canada Trans., v. 43, p. 157–184.

———, 1966, Did the Atlantic close and then reopen?: Nature, v. 211, p. 676–681.

———, 1967, Theories of building of continents, *in* GASKELL, T. F. (ed.), The earth's mantle: London, Academic Press, p. 445–473.

WYLLIE, P. J., 1973, Experimental petrology and global tectonics—a preview: Tectonophysics, v. 17, p. 189–209.

ZONENSHAIN, L. P., 1972, Similarities in the evolution of geosynclines of different types: 24th Intnat. Geol. Cong., Sec. 3, p. 494–502.

My first field
sin, sixty miles
stratigraphic rese
was in correlatio
St. Lawrence, a
brian) in the vi
when E. O. Ulr
longed in differe
summer I had st
northern Iowa u
M. Smith, then P
sin. And my doct
and limestones i
neighboring state
could hold the sy
the University of

I am particula
for his having a
a pleasure to vis
and former stude
uing progress of
sediments. The
cellent summarie
would be somew
ment briefly on
the formulation
cation of geosyn
givings on some

The view of
North America
of the so-called
morphic and ig
synclines from t
interest to trace
(Kay, 1967).
exceptional that
model. Their sit
maps as embaym

My interest in
with the discove
canic ash beds
North America
beds in the Dec
Iowa. At first t
notion, which I
there had been