PLATE TECTONICS AND TECTONIC MAPPING

by

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A tectonic map attempts to portray the origin and evolution, in space and time, of a region. While plate tectonic concepts have been successfully applied to the Phanerozoic and Proterozoic, their application to the Archean is still under debate. The advent of plate tectonic theory heralds a new generation of tectonic maps for most of the Earth's surface, namely that part underlain by Phanerozoic and Proterozoic rocks. It may be necessary, however, to base tectonic mapping of Archean terrains upon an alternative tectonic model.

Introduction

In tectonic mapping of the Province of Nova Scotia, Canada, using plate tectonic theory, three hierarchical categories of rocks have been recognized: zones, stages and elements (Keppie, 1979; in press).

A tectonic zone is characterized by the nature of the underlying crust (continental, transitional or oceanic) at the time the rocks were formed and is closed in time by an orogeny. An exception is the present phase of tectonic evolution which is incomplete. A tectonic stage is a phase of tectonic development forming part of a tectonic zone and is characterized by an association of tectonic elements. The following stages are recognized: stable, rift, atlantic, pacific and transpression. These terms are not capitalized so as to avoid confusion with present day processes in the Atlantic and Pacific regions, for example.

A tectonic element is a certain, specific, well-defined tectonic environment, characterized by a distinct tectono-stratigraphic or tectono-plutonic rock unit that is part of a tectonic zone or stage. Examples of tectonic elements are continental shelf, forearc basin, marginal basin and magmatic arc. These tectonic units may exist side by side at any point in time, and conversely any area may belong to several different tectonic units as it evolves through time.

The scale of a tectonic map controls the degree of subdivision shown. Thus, on small-scale maps only tectonic zones may be shown, intermediate-scale maps may include tectonic zones, stages and possibly combinations of elements, and large-scale maps can portray all three categories. Structural elements, including fold traces, foliations and faults, can also be plotted on a tectonic map as can structural contours in undeformed or mildly deformed basins and the axes of gravity and magnetic anomalies.

Tectonics and Structural Geology

Before embarking on a discussion of tectonic mapping, it is essential to clarify the terms "tectonics" and "structural geology". Although structural geology is adequately defined in texts and geological dictionaries, the definition of tectonics ranges from being synonymous with structural geology (e.g. Schieferdecker, 1959) to statements that tectonics is an independent branch of geology (e.g. Bates and Jackson, 1980). The definitions preferred by this author are as follows:

Structural geology deals with the form, arrangement and internal structure of rocks, and especially with the description, representation and analysis of structures, chiefly on a moderate to large scale. It follows that a structural map depicts the age and orientation of structures such as folds, faults or foliations and is predominantly objective.

Tectonics is the study of the broad architecture of the outer part of the Earth, the regional assembling of structural features and tectonic units, and their mutual relations, origin, and historical evolution (Bates and Jackson, 1980). Thus, a tectonic map illustrates and interprets the evolution of the architecture of the Earth's crust in time. Tectonic

mapping involves a degree of subjectivity which becomes more objective as the properties of individual tectonic units are better understood. Tectonic maps display tectonic units in their present locations and are considerably more objective than pre-Mesozoic palaeotectonic maps which involve palinspastic reconstructions based on relatively limited data.

Tectonic maps are currently available for most countries in the world, and a history of tectonic mapping can be found in King (1969) and Scheibner (1972). According to the above definitions, some of these so-called tectonic maps should be described as structural maps. The first genuine tectonic map was produced by Argand (1924); considerable progress has been achieved since then. Most of these tectonic maps, however, have been based on the outdated geosynclinal theory (Coney, 1970), including many of those produced since the advent of the plate tectonic theory nearly two decades ago.

Several recent maps based on plate tectonic theory are the Tectonic Map of Canada (Douglas, 1973), the Tectonic Map of New South Wales (Scheibner, 1974, 1976), the Tectonic Map of the Indonesian Region (Hamilton, 1978, 1979), and the Tectonic Lithofacies Map of the Appalachian Orogen (Williams, 1978). These maps show considerable variation in their legends, probably in large part due to the rapid evolution of plate tectonic theory. A more formal scheme, based on plate tectonic theory, has been devised for the Tectonic Map of Nova Scotia (Keppie, in press).

Plate Tectonic Theory

Plate tectonic theory was developed for the ocean basins, and its rules can be applied quantitatively only to the Mesozoic and Cenozoic history of oceanic plates for which such information on spreading velocities, first motion solutions, and orientations of transform faults is available (Le Pichon et al., 1973). Nevertheless, plate tectonic theory has been applied qualitatively to many continental areas around the world. Most of these models explain the geology of areas which were, or are, continental margins, that is, passive continental margins or consuming plate boundaries where orogens are formed.

Such models form the essential part of any tectonic map because, once an area is "cratonized", it may become covered by relatively simple platformal cover rocks. With the increase in the diversity and amount of geological data relating to Mesozoic/Cenozoic plate margins and older parts of the geological record, plate tectonic models become more objective. It should be stressed that data from all subdisciplines of solid-earth science are essential to an integrated model, which has been generated for orogens as old as the earliest Proterozoic (Hoffman, 1980). Cogent theoretical arguments have been put forward for plate tectonics in the Late Archean (Burke et al., 1976); however, a consensus has not been reached (Kerr, 1978). Burke and Dewey (1973) have proposed that the plate tectonic regime was preceded by a permobile phase characterized by rapid convective circulation in the mantle and a thin lithosphere. If this is the

case, then a modified tectonic model is a necessary prerequisite for producing a tectonic map for most of the Archean.

Principles of Tectonic Mapping

A tectonic map portrays at least three types of information: tectonic units, structural units and elements, and the shape of basins. In order to arrive at the most objective tectonic interpretation of any unit, it is necessary to compile and analyze as complete a range of geological parameters as possible, including stratigraphy, paleontology, structure, volcanism, plutonism, metamorphism, geochronology, and geophysics. These parameters are initially compiled in correlation charts or time/space diagrams. This allows tectono-stratigraphic units to be defined which, following deposition, are transformed by deformation and metamorphism.

Of the recent tectonic maps based upon plate tectonic theory, a variety of tectonic units are shown for stratified rocks such as oceanic crust, melange, outer-arc basin, foreland basin, platform cover, continental slope and rise, but, generally plutonic rocks are not classified tectonically. Only on the Tectonic Map of New South Wales (Scheibner, 1974, 1976) is there a systematic attempt to categorize these tectonic units into tectonic stages, provinces and realms. Unfortunately, little distinction is made between these higher ranking tectonic units.

In the present scheme, three hierarchical categories of tectonic units are recognized: zones, stages and elements (Fig. 1, Table 1). Tectonic mapping proceeds by first defining the tectonic elements, which are then grouped into higher ranking tectonic units, stages and zones.

Figure 1: Tectonic zones, stages and elements. Note that tectonic stages can also co-exist in space at any one time.

Tectonic Elements

Tectonic elements are defined by their geological properties and may be grouped into the higher ranking tectonic units, stages and zones. Many names abound in the literature for tectonic elements and some that may be used in tectonic mapping are illustrated and tabulated with their properties (Fig. 1, Table 1). This list is open ended; others may be included as they become defined. Some of these tectonic elements require more precise definitions than current usage allows, but are not included here.

Tectonic Stages

Although a large number of stages in tectonic evolution have been recognized in modern plate tectonic settings (Burke and Whiteman, 1973; Dewey, 1969; Dewey and Horsfield, 1970; Keen, 1979; Dickinson, 1977), only the main stages can be clearly identified in ancient orogenic belts. Others may be classified as sub-stages. For example, if subduction of the mid-oceanic ridge can be recognized, it would be possible to separate out a mediterranean sub-stage of the pacific stage (Dewey, 1969). However, it is difficult at our present level of understanding to define unequivocal boundaries between sub-stages, and so they are not used in the present scheme.

The stable tectonic stage is represented by the cratonic cover deposits. The rift tectonic stage is characterized by aulacogens, half-grabens and rift valleys and the terrestrial deposits therein, and alkalic volcanism (Freund, 1965; Cherkunov, 1967; Illies, 1969; Burke and Whiteman, 1973). The boundary between the stable and rift stages is placed at the initiation of the bounding faults. These two stages occur in the continental and transitional tectonic zones.

The present spreading of the Atlantic Ocean is typical of the atlantic tectonic stage, and is characterized by continental shelf and rise and ocean floor deposits. The beginning of the atlantic stage is defined by the beginning of spreading, that is the appearance of new oceanic crust in an axial dyke accompanied by plateau basalts and dyke swarm feeders. This tectonic stage may occur in all three tectonic zones.

The pacific tectonic stage is typified by the present Pacific Ocean in which the mid-oceanic ridge, in places, has been subducted. It is characterized by island arc complexes and cordilleran-type continental margins (Dewey and Horsfield, 1970). The initiation of the pacific stage is defined by the start of subduction, that is the formation of Franciscan facies melanges followed by calcalkaline volcanicity. This tectonic stage may occur in all three tectonic zones.

The transpression tectonic stage is characterized by deposits of molasse in foredeeps, intradeeps and backdeeps, alkalic-tholeiitic volcanism, and ring complexes and calderas, which are usually deformed by transpression (folding and transcurrent faulting) but are rarely metamorphosed. During this stage the relative motion may vary from perpendicular, through oblique to parallel, and depending on the shape of the margin, (S or Z) zones of compression or tension may form. The start of the transpression stage is defined by the time of suturing and the beginning of molasse deposition. This tectonic stage may also occur in all three tectonic zones.

Although the tectonic stages have been described in a sequence which might be considered an ideal tectonic cycle, no determining sequence of events can be assumed in plate tectonic theory because, for example, crustal separation can occur any time in any place (Coney, 1970). It should also be noted that the boundaries between tectonic stages are often diachronous.

Tectonic Zone

The oceanic tectonic zone (similar to oceanic realm and tectonic province of Scheibner, 1976) is characterized by

TABLE 1
Classification and Characteristic Geological Properties of Tectonic Stages and Tectonic Elements

TECTONIC STAGE Map notation indicated Basic colours	TECTONIC ELEMENT Map notation indicated, shades of basic colours. Other elements are possible	CHARACTERISTIC GEOLOGICAL PROPERTIES				
STABLE(s)	Epicontinental basin Terrestrial basin Platform cover	SEDIMENTARY Shallow marine Continental Thin marine &/or continental	IGNEOUS Rare alkalic volcanism &/or plutonism	STRUCTURAL Generally absent or weak: domes, basins, monoclines	METAMORPHIC Absent	MINERALIZATION Fe-Mn, oil & gas U, non-metallic Sn-F-Nb
END OF OROGENIC ACTIVITY						
TRANSPRESSION (t)	s type plutons is type plutons	-	Granite, grandiorite, Alaskan-type gabbro-peridotite intrusives	Calderas, ring complexes Concentric shape	-	Sn-W-F-U Ti-Fe-Cr-Pt
	Volcanic rift Backdeep Intradeep, intramontane depression Foredeep Foreland basin	Molasse: terrestrial to shallow marine	Alkalic- tholeiitic bimodal volcan- ism, some calcalkalic	Deformed with s next to the orogen, else- where undeformed; transcurrent faulting, paratectonic	Low tempera- ture burial metamorphism may occur	Pb-Zn-Cu-U-Ag
INITIATION OF SUTURING AND APPEARANCE OF MOLASSE						
PACIFIC (p)	Marginal or backarc basin Interarc basin Periarc basin Oceanic crust layers 1, 2 & 3 Upper Mantle Oceanic seamount	Volcaniclastic flysch, pelagic sediments on oceanic litho- sphere	Ocean floor & mid-ocean ridge tholeiitic basalts, gabbroic intrusives, ophiolite	Variable: gentle to intense deformation	Low grade to regional high T/P	Cyprus-type Cu-Fe, Au-Ag, Cu-Ni-Pt
	Peripheral basin Retro-arc basin	Wildflysch, flysch, shale	Shoshonitic volcanics, alkalic plutons	Nappe emplacement, gentle-intense deformation	Grade: Low- high T/P	Pb-Zn-Cu-U
	i type Magmatic arc	Flysch	Calcalkaline an- desites, rhyolites & basalts, & syn- tectonic pluton- ism	Generally intense polyphase, sometimes gentle deformation, orthotectonic	Low grade to regional high T/P & medium T/P	Porphyry Cu-Mo & Au, Sn-W-Ag Sb
	Volcanic arc rift in volcanic & magmatic arcs	Submarine &/or subaerial volcaniclastics, greywacke	Ignimbrites, some calcalkaline volcanics	Graben: variable subsequent deformation	Variable	Kuroko-type Cu-Pb-Zn
	Volcanic arc Remnant arc	Submarine &/or subaerial volcaniclastics, greywacke	Volcanism: (i) Shoshonitic (ii) Calcalkaline (iii) low-K tholeiitic syntectonic plutonism	Variable: gentle to intense deformation. Orthotectonic	Low grade to regional high T/P & medium T/P	Porphyry Cu-Au Besshi-type Cu-Fe, Hg, Au, S-Fe
	Forearc basin	Pyroclastics, clastic terres- trial & shelf sediments, bio- genic sediments	Pyroclastics	Variable: gentle to intense deformation	Subgreenschist facies	Au Hg
	Trench complex	Accretionary prism of flysch, olistostromes, oceanic sediments & dismembered ophiolite, melange	Oceanic layer 2, mid-ocean ridge basalts	Concave upward, imbricate thrusts. Variable degree of folding	Blue schist facies, high P/T	Cyprus-type Cu-Fe, Hg, Ag
START OF SUBDUCTION, APPEARANCE OF SUBDUCTION COMPLEX AND CALCALKALINE VOLCANISM						
ATLANTIC (a)	Microcontinent Microcontinental submarine platform	Relatively thin, shallow water to moderately deep water sediments on drowned plateau	Rare	Variable: gentle to intense deformation	Low grade to regional high T/P & medium T/P	
	Oceanic seamount	Exotic shallow water sediments	Alkalic-tholeiitic oceanic island volcanism	Variable: gentle to intense deformation	Low grade	
	Oceanic lithosphere, ophiolite Oceanic crust layers 1, 2 & 3 upper mantle mid-oceanic ridge	Pelagic sediments on oceanic lithosphere	Mafic, mor, abyssal tholeiitic volcanics, sheeted dyke complex, basic & ultrabasic complex	Undeformed to highly deformed	Zeolite- greenschist (-amphibolite) facies	Cyprus-type Cu-Pb-Zn, Fe, Mn, As, B, Zn, Ag, Hg in sediments, Podiform Cr, Ni, Pt
	Continental slope & rise	Turbidite fans	Rare	Intense deformation	Low grade to high T/P	Oil & gas
	Marginal plateau	Shelf edge car- bonate bank or reef, shoals	-	Variable	Low grade to high T/P	Oil & gas
	Continental shelf Basaltic plateau	Meritic, littoral & sub-littoral sediments	Tholeiitic plateau basalts at base	Fold & thrust belt	Absent-Low grade	Metal-rich muds (Zn, Cu) Mississippi Valley Pb-Zn- Ba, Oil & Gas
START OF SPREADING ASSOCIATED WITH AXIAL DYKE AND PLATEAU BASALTS						
RIFT (r)	Alkalic intrusives Volcanic rift	-	Alkaline volcanism & intrusives, carbonitites, kimberlites	-	-	Sn-F-Nb Ta-Nb-P, Ba-F- REE
	Rift valley Aulacogen	Terrestrial to shallow marine, evaporites	Alkalic mainly in rift valleys	Faulting	burial meta- morphism	Sullivan-type Pb-Zn-Ag, Mississippi Valley Pb-Zn- Ba, Oil & Gas
DEEP CRUSTAL FAULTING						
STABLE(s)	As above	As above	As above	As above	As above	As above

Note that no cycle of tectonic stages is implied because many lines of evolution can occur in plate tectonics.

presence of oceanic lithosphere (oceanic crust and upper mantle). Its thickness and the depth of the ocean increases proportionately away from the mid-oceanic ridges according to its cooling rate and age (Rona, 1973). The average thickness of the oceanic lithosphere is 70 km. The oceanic crust is generally made up of three layers: layer 1, pelagic and hemipelagic sediments up to about 500 m thick; layer 2, submarine abyssal tholeiitic basic flows 100-2000 m thick; and layer 3, greenschist facies metabasalts, amphibolites and gabbros about 5 km thick. Sheeted dyke complexes are typical of the boundary between layers 2 and 3.

The **continental tectonic zone** (similar to the continental realm and epi-cratonic tectonic province of Scheibner, 1976) is characterized by cratonic covers on platforms overlying the continental lithosphere. The continental lithosphere, with an average thickness of 150-250 km, is composed of continental crust (~ 35 km) made up of an upper "granitic" crust and a lower "basaltic" crust of overlying upper mantle possibly composed of depleted residual peridotite (Ringwood, 1969).

The **transitional tectonic zone** (similar to the transitional realm, and pre-cratonic and transitional tectonic provinces of Scheibner, 1976) is characterized by rocks deposited where the nature of the underlying crust is transitional between continental and oceanic. Such transitions generally occur either on passive continental margins (e.g. Atlantic) or in active marginal mobile zones where unevenly distributed blocks of oceanic and continental crust often occur. Compared with the relatively simple geological record in oceanic and continental tectonic zones, the transitional zone has a varied and complex record typical of orogenic belts. Characteristic tectonic elements include rift, continental shelf and rise, calc-alkaline, "i"-type volcanic and magmatic arcs; intradeep and backdeep; and transpressional "s" and "is"-type plutonism (Chappell and White, 1974). These rocks exhibit a complete range of deformation and metamorphism.

These three tectonic zones can exist side by side and their geographic boundaries can be identified. The location of these boundaries only changes radically following orogenesis. Thus, tectonic zones are also bounded in time by orogenies.

The Glossary of Geology (Bates and Jackson, 1980) defines orogeny as the process by which structures within mountain areas were formed, including thrusting, folding and faulting in the outer and higher layers and plastic folding, metamorphism and plutonism in the inner and deeper layers. It usually occurs over a finite period of time, is fundamentally related to consuming plate margins and the accretion of terranes, and extends over a large area (Cebull, 1973). The end of an orogeny is used here to define the boundary between tectonic zones in time. A tectonic zone is named after the orogeny

which terminates it. While it is recognized that orogenesis may die out gradually making the choice of a boundary somewhat arbitrary, experience has shown that a clear distinction generally can be made between molasse deposits and overlying cover rocks.

Map Representation

On the Tectonic Map of Nova Scotia, each tectonic stage is assigned one or more basic colours and each tectonic element bears a shade of colour dependent upon the stage to which it belongs. Structural elements, fold traces, foliations and faults are also included.

Fold traces and foliations are colour-coded according to the orogeny in which they formed. Faults are black with letters adjacent to the movement symbols to indicate the age of movement. Dykes are also plotted on the map because they indicate tensional stresses in the crust.

In undeformed or mildly deformed basins, structure contours preferably on its base or alternatively on some higher stratigraphic horizon are used to illustrate the shape of the basin. Axes of Bouguer gravity anomalies, both highs and lows, as well as axes of high magnetic anomalies may also be shown.

Conclusions

The advent of plate tectonic theory produced a revolution in the earth sciences (Wilson, 1968) so profound that all aspects of the science of geology required thorough re-evaluation in light of the new theory. Tectonic mapping is one of the more direct applications, but few such maps have been published to date. This may be partly due to rapid evolution of plate tectonic theory; however, in the two decades since its advent, the basic tenets have become more precisely defined. A new generation of tectonic maps based on plate tectonic theory should be prepared. As the geological properties of tectonic elements become better defined, so tectonic mapping will become more objective.

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