SEGMENTS AND SUPER-UNITS IN THE COASTAL BATHOLITH OF PERU [1]

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ABSTRACT

By analogy with rock-stratigraphic nomenclature the plutonic rocks of the linear Coastal Batholith of Peru can be grouped into units (formations) which can further be grouped into super-units (groups). Such an hierarchical system enables the Coastal Batholith to be divided into three compositionally distinct segments 200, 400, and 900 km in length. Segmentation is thought to reflect discontinuities in a subduction zone, with magmatism in each segment possessing its own unique episodicity of emplacement and spatial distribution. Within each super-unit differences in the time of arrival of the magmas in the upper crust produce magmatic diachronism. On the basis of an upper mantle/lower crustal melting hypothesis it seems that within each segment, which takes of the order of 70 m.y. to emplace, the super-units are the product of separate melt cells, each of which exists spasmodically over a period of *ca.* 10 m.y. The melt cells provided progressively more acidic magma with time, whilst decreasing in areal extent.

The concept that cordilleran batholiths are composed of a limited number of specific rock types was first explicitly stated by Larsen (1948) who, in describing the intrusive rocks of south-west California wrote that "about three-fourths or more of the batholith is made up of about six rock types. The main types are present in many separate bodies and most of them are present along the whole length of the batholith in California."

In the Sierra Nevada, Bateman and Dodge (1970) have recognized eight plutonic sequences each of which contains rock units that range from basic to acid in composition, and they suggested that with further study it might be possible to consider these sequences in rock-stratigraphical terms. More recently Cobbing and Pitcher (1972) working in Peru have similarly described assemblages of consanguineous rock units which they termed super-units. Subsequent work in Peru has now shown that these super-units have a longitudinal extent of many hundred kilometers. It is therefore evident that the occurrence of a limited number of granitoid rock types over widespread areas, though disposed in many separate plutons, is a common feature of cordilleran batholiths.

In order to describe a batholith in these textural and compositional terms we find a need to employ a nomenclature divorced from structural terms such as dyke, sill, sheet, stock, pluton, or the assemblage of these in a plutonic complex. Thus rocks with identical petrographic features are referred to as a unit. A number of different units, often closely associated in time and space, can show so clear a kinship that they can be grouped into a super-unit.

The hierarchical division suggested depends absolutely upon a clear definition of each *unit*. Thus to be unequivocably assigned to a particular unit, rocks from within the same linear batholith should have the same relative age based on clear cross-cutting contact relationships. In addition they should show the same modal variations to a similar degree, the same texture and fabric, the same relationship to the associated dyke swarms, and similar xenolith content and character. Confirmation should be sought from aspects of the geochemistry and from geochronology, but here one is faced with the logistic difficulty of determining the age of rocks of the same unit distributed in hundreds of separate plutons.

Such a usage works well in Peru where the Western Cordillera is flanked for some

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1500 km, as if along a single, deep-seated structural lineament, by the 100 to 30 m.y.-old Coastal Batholith (Cobbing and Pitcher 1972, Pitcher 1974, Myers 1975, Pitcher and Bussell 1977). The intrusives are perfectly exposed in desert terrain which greatly facilitates the mapping of the contacts between the different units. In such favorable conditions the component units of the batholith, despite being disposed between many separate plutons, can be mapped on the same basis as stratigraphic formations. This is because the relative age relationships between the various lithological units, as established in any one traverse, remain substantially the same for any other traverse.

A good example of a unit of the Coastal Batholith is that of Pampa Ihuanco (see Cobbing and Pitcher 1972, p. 432), a coarse grained granodiorite-monzogranite possessing an even texture, a color index of 6-12, and with biotite and hornblende equally represented. Such a unit occurs throughout a 400 km long stretch of the batholith but always in close association with a number of other units, varying from quartz diorite to leuco-monzogranite, which together make up the consanguineous Santa Rosa super-unit. The essence of the kinship in this case is the consistent spatial and temporal association of all the constituent units, the progressive evolution of both the mineralogy and the textural interrelations, especially of the quartz and potash feldspar, and the maintenance of similar granularity and aphyric character.

As will be seen from the above a unit is defined by an assemblage of criteria any single one of which, e.g., mode and hence rock name, is inadequate in itself. Hence we prefer to use a term without nomenclatural significance. In view of the need for an hierarchical system we believe it logical to use super-unit for an assemblage of related units. The term *suite* does not seem adequate to describe a grouping of units in our sense, but *sequence* (as used by Bateman and Dodge, 1970) might often be applied. It has been avoided simply to emphasize the hierarchical progression with the term *unit* being somewhat analogous to the lithostratigraphic term *formation*: similarly, *super-unit* is analogous to *group* in the stratigraphic sense.

On such a basis of division we have identified seven super-units and a number of unassigned units which, together, constitute the major part of a 400 km stretch of the Coastal Batholith outcropping between Lima and Chimbote. These comprise three early super-units designated, in order of decreasing age: Patap (gabbro), Paccho (diorite-tonalite), and the Santa Rosa (quartz diorite-tonalite-granodiorite-monzogranite); these are followed by an essentially coeval trio of granitoid super-units, San Jerónimo (monzogranite-syenogranite), La Mina (granodiorite) and Puscao (granodiorite-monzogranite), and, latest of all, the Sayán-Pativilca super-unit (monzogranite). These super-units are variously represented but commonly two, sometimes three, form the bulk of outcrops in a single cross-traverse, the Santa Rosa always predominating. There is also a variation in the extent of each unit along the axis of the batholith but elements of the above assemblage form the bulk of the batholith between Lima and Chimbote.

It is of considerable interest that this particular assemblage of units and super-units does not persist much farther north than the Rio Santa near Chimbote or much farther south than Lima. Its place is taken, to the north and south, by assemblages of granitoids with different characteristics and only the ubiquitous early gabbros are common to all. The different rock units which appear in the valley of the Rio Santa (pers. comm. A. Bussell), remain to be studied, especially as to whether they represent a specific assemblage extending towards Trujillo. However, some 400 km to the south, specifically in the Quebrada de Tinajas to the east of Lima (fig. 1), there is a similar marked change in the nature of the super-units and this we have mapped out in some detail.

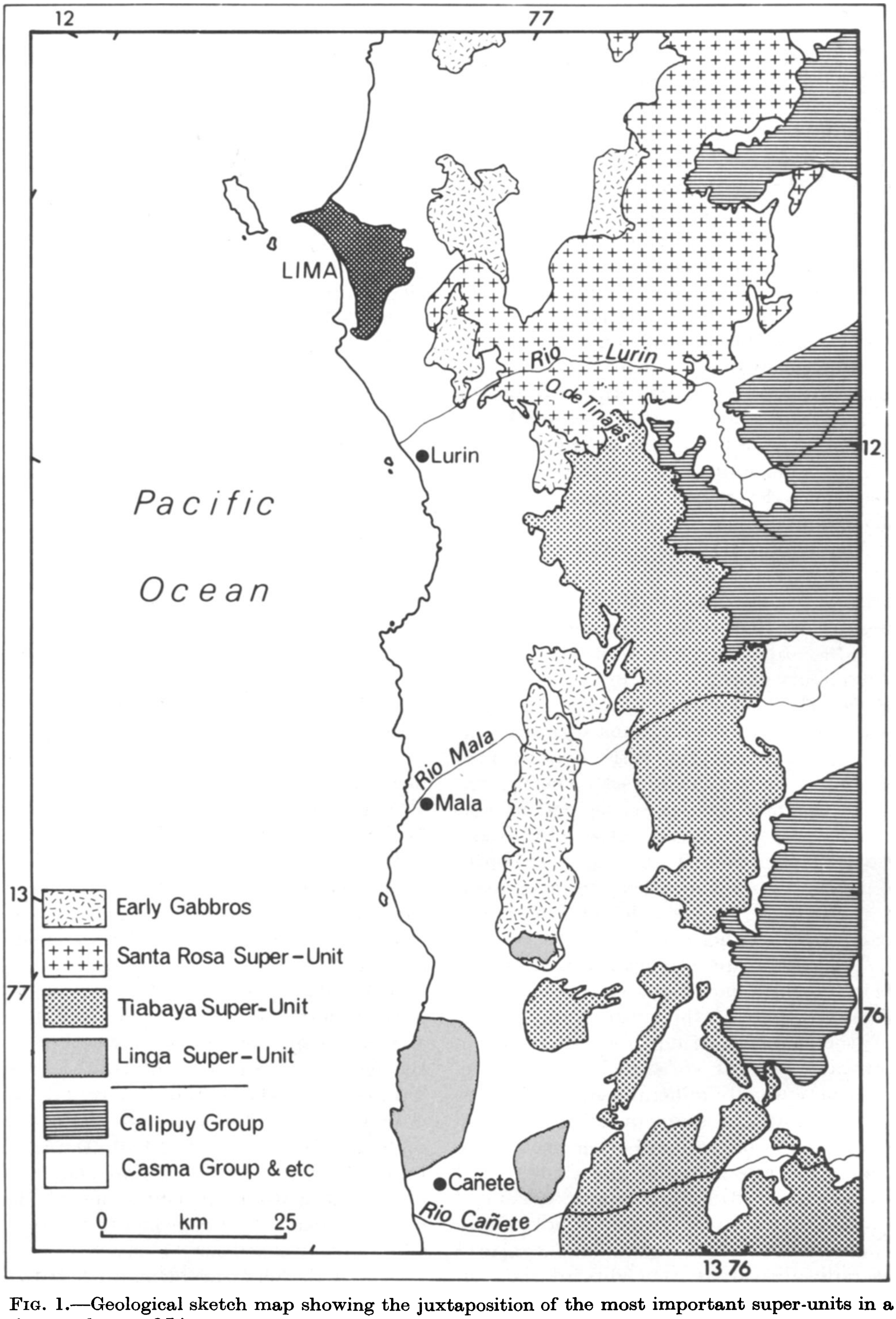

FIG. 1.—Geological sketch map showing the juxtaposition of the most important super-units in a region southeast of Lima.

The two, recently recognized super-units which abruptly take over from the Santa Rosa dominated assemblage near Lima form the bulk of outcrops for the remaining southern 900 km of the batholith proper. These are designated the Tiabaya (tonalite-monzogranite) and Linga (monzogabbro-quartz monzonite) super-units named, respectively, after localities near Arequipa. In fact in the Arequipa area the various rocks have been described in detail (Jenks and Harris 1953) and assigned to specific groups, equivalent to our super-units, by Stewart (1968). It is the latter's Grupo Linga and Tiabaya Granodiorite which we have now recognized as forming major super-units extending along some 800 km and 900 km, respectively, of the length of the batholith.

The main outcrop of the Coastal Batholith is therefore clearly divisible into at least two, and possibly three, great compositionally contrasted *segments*. We propose to refer to the southern as the Arequipa segment (including the Arequipa Batholith of Stewart, *loc. cit.*), the central, and best known, as the Lima segment, and the northern, as yet little known, provisionally as the Trujillo segment (fig. 2). That the batholith is so segmented and that each part is characterized by a particular assemblage of super-units abruptly separated from the others, is a concept which might be applicable to linear batholiths in other cordilleran situations.

The important change in rock types between the Lima and Arequipa segments is also reflected in the nature and strength of the mineralization, for whereas the central segment of the batholith is relatively weakly mineralized, the outcrop of the southern segment is covered by innumerable mines, exploiting principally copper but also gold and iron (Bellido and De Montreuil 1972). Stratigraphical control confirms that this difference is not simply due to the segments having been emplaced at radically different heights in the volcano-sedimentary pile. Furthermore recent work has shown that specific types of mineralization are associated with distinct super-units (Hudson 1974).

Such a compositional segmentation of the batholith may prove to be a reflection of differences in both structure and composition of the crust. A regional tectonic segmentation of the Andes has been noted by Sillitoe (1974) who, in relating these to discontinuities in the subduction zone, suggests that magmatism in each sharply demarcated segment will necessarily possess its own unique episodicity and spatial distribution (*cf.* also Swift and Carr 1973). In fact the most important change in rock units, that located near Lima, corresponds in general terms to the Pisco-Abancay deflexion zone where the dip of the present Benioff zone steepens from some 10° (in northern Peru and Ecuador) to 30° (Stauder 1975, Mégard and Philip 1976), though how abruptly is not known. If the flexure in the Benioff zone had been in existence during the Cretaceous then it offers an explanation for this particular change in composition along the batholithic lineament on the basis that a wedge of upper mantle material may possibly be present between the lower crust and the Benioff zone and directly beneath the Arequipa segment in southern Peru (*cf.* Barazangi and Isacks 1976).

It is appropriate here to consider the time intervals over which the segments and super-units were assembled in the upper crust (*cf.* Pitcher 1975). The segments appear to be broadly contemporaneous and the time-span for the Lima segment is of the order of 70 m.y. (Stewart et al. 1974, Wilson 1975), perhaps somewhat less for the Arequipa segment, but there is some indication that plutonic activity was episodic within the confines of any *one* segment (Bussell et al. 1976). Dates obtained from the various component units of the Santa Rosa super-unit suggest that the time-span of emplacement of a single super-unit was at least 11 m.y.

One of the chief problems to be solved is whether the time of intrusion of any one super-unit remains constant along the axis

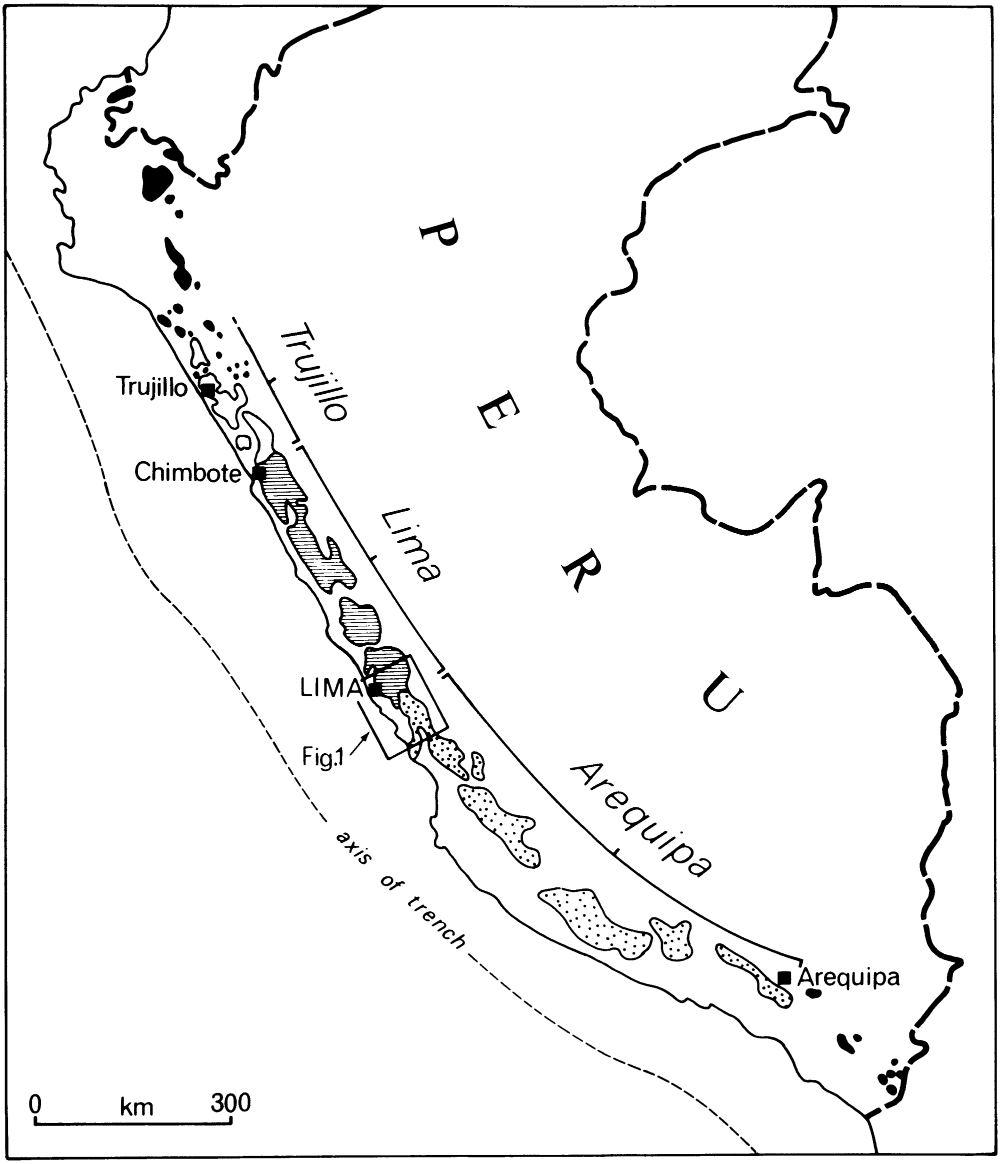

FIG. 2.—The major segments of the Coastal Batholiths of Peru and its extensions as isolated plutons.

of a segment, even between contiguous structural lenses, but as yet there are insufficient age determinations for such a test. Careful mapping of the Lima segment shows that the gross chronological sequence, *viz.* Patap, Paccho, Santa Rosa, early granites of the ring-complexes, late granites of the Sayán-Pativilca type, remains unchanged. However between the three units of the ring-complex granites local differences are revealed in the relative times of intrusion between rock types which otherwise have identical field characteristics. Thus in the Huaura ring-complex (Bussel et al. *loc. cit.*) a ring-dyke first filled by magma of San Jerónimo type was later invaded by Puscao magma, yet some 100 km farther north in the Fortaleza ring-complex the relationship is reversed (Knox 1974, Myers 1975), so much so in fact that a 5 m.y. difference in radiometric ages (K-Ar) has been recorded (Wilson *loc. cit.*). Evidently we are dealing with a kind of magmatic diachronism.

Notwithstanding all these complications and comparative lack of data the available geochronology does suggest that the differing magma types of the different super-units were produced on separate occasions, a similar view to that held by Presnall and Bateman (1973) who propose separate and wholesale melting episodes for each of their sequences in the Sierra Nevada. It is possible to account for minor reversals in order of intrusion by invoking differences in the time of arrival of globules of a particular magma-type in the upper crust.

A partial model is that, throughout tens of millions of years, magmas were repeatedly generated within a narrow zone parallel to the continental plate edge, a zone localized by the deep penetration of a major fault zone (Pitcher and Bussell 1977). We favour a crustal melting hypothesis in which, consequent on the emplacement of great volumes of mantle-derived basic magma into the base of the crust, melting processes generated the early granitoids. Such melting seems to have occurred in separate cells of the dimensions of the present segments and then, it seems, the melt zones contracted areally with time. For example the earlier units of the Santa Rosa super-unit (*ca.* 95–84 Ma) occupy the whole of the Lima segment, the later units (*ca.* 72 Ma) almost the same length but in much lesser volume, the Puscao (*ca.* 65 Ma) 300 km, and the Sayán-Pativilca (*ca.* 61–34 Ma) 100 km. We suspect, in fact, that each segment represents a rhythmic sequence of magma generation and differentiation. A central problem is how this long-standing episodic process was sustained after the initial heating.

It is likely that each super-unit magma was produced under a different $P\text{-}T\text{-}X_{H_2O}$ regime, possibly as a result of a changing depth of generation within the crust with time. Draughts of magma arising as globules from each linear melt-zone, though necessarily bearing the geochemical stamp of a particular magma type, might well have disengaged at different times along the zone. However, since each super-unit tends to have its own characteristics, even down to textural details, the conditions of ascent and hence differentiation and final consolidation of any given original magma type must have been remarkably stereotyped. This suggests an ascent overwhelmingly controlled by some fundamental physical property of the original magma and evolving liquid.

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REFERENCES CITED

BARAZANGI, M., and ISACKS, B. L., 1976, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America: Geology, v. 4, p. 686–692.

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

BELLIDO, E., and DE MONTREUIL, L., 1972, Aspectos generales de la metalogenia del Perú: Geol. Econ. Serv. geol. Min. Perú, No. 1, p. 149.

BUSSELL, M. A.; PITCHER, W. S.; and WILSON, P., 1976, Centred complexes of the Peruvian Coastal Batholith: a long-standing sub-volcanic regime: Can. J. Earth Sci., v. 13, p. 1020–1030.

COBBING, E. J., and PITCHER, W. S., 1972, The Coastal Batholith of Peru: Geol. Soc. Lond. Jour., v. 128, p. 421–460.

HUDSON, C., 1974, Metallogenesis as related to crustal evolution in southwest and central Peru: Unpubl. Ph.D. thesis, Univ. Lverpool, p. 245.

JENKS, W. F., and HARRIS, E. G., 1953, Plutonics near Arequipa as a petrologic sample of the coastal batholith of Peru: Soc. geol. Peru Bol., v. 26, p. 79–94.

KNOX, G. J., 1974, The structure and emplacement of the Rio Fortaleza centred acid complex, Ancash, Peru: Geol. Soc. Lond. Jour., v. 130, p. 295–308.

LARSEN, E. S., 1948, Batholith and associated rocks of Corona, Elsinore and San Luis Rey Quadrangles, Southern California: Geol. Soc. Amer. Mem. 28, p. 182.

MEGARD, F., and PHILIP, H., 1976, Plio-Quaternary tectono-magmatic zonation and plate tectonics in the Central Andes: Earth and Planetary Science Letters, v. 33, p. 231–238.

MYERS, J. S., 1975, Cauldron subsidence and fluidisation: mechanisms of intrusion of the Coastal Batholith of Peru into its own volcanic ejecta: Geol. Soc. Amer. Bull., v. 86, p. 1209–1220.

PITCHER, W. S., 1974, The Mesozoic and Cenozoic batholiths of Peru: Pacific Geol., v. 8, p. 51 62.

——— 1975, On the rate of emplacement of batholiths: Geol. Soc. Lond. Jour., v. 131, p. 587–591.

———, and BUSSELL, M. A., 1977, Structural control of batholithic emplacement in Peru: a review: Geol. Soc. Lond. Jour., v. 133, p. 249–256.

PRESNALL, D. C., and BATEMAN, P. C., 1973, Fusion relations in the system $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-SiO_8-H_2O and generation of granitic magmas in the Sierra Nevada Batholith: Geol. Soc. Amer. Bull., v. 84, p. 3181–3202.

SILLITOE, R. H., 1974, Tectonic segmentation of the Andes: implications for magmatism and metallogeny: Nature, London, v. 250, p. 542–545.

STAUDER, W., 1975, Subduction of the Nazca Plate under Peru as evidenced by focal mechanisms and by seismicity: Jour. Geophys. Research, v. 89, No. 8, p. 1053–1064.

STEWART, J. W., *in* GARCIA, W., 1968, Geología de los cuadrángulos de Mollendo y La Joya: Serv. Geol. Min. Perú, Bol. 19, p. 93.

———; EVERNDEN, J. F.; and SNELLING, N. J., 1974, Age determinations from Andean Peru: a reconnaissance survey: Geol. Soc. Amer. Bull., v. 85, p. 1107–1116.

SWIFT, S. A., and CARR, M. J., 1973, The segmented nature of the Chilean deep seismic zone: Conference on Geodynamics, Int. Union. Geodesy, Geophys. Lima 1973, GGD-24.

WILSON, P. A., 1975, K-Ar age studies in Peru with special reference to the emplacement of the Coastal Batholith: Unpubl. Ph.D. thesis, Univ. Liverpool, p. 299.

NEW HISTORICAL DATA ON CRUSTAL SUBDUCTION[1]

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ABSTRACT

It appears that five years before Ampferer, P. J. Holmquist recognized the process of large-scale underthrusting of the entire basement of the foreland along a localized zone as a cause of folding and thrusting in orogenic belts. He inferred that the foreland must have descended beneath the orogen to considerable depths, but did not offer any mechanism of getting rid of the underthrusted material. In the same year Eduard Suess supported Holmquist's interpretation, but also added that his mechanism for orogenic deformation was not a final solution as it only transported the problem of shortening in the crust to a deeper level in the Earth.

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INTRODUCTION

The history of the concept and/or term subduction, both crustal (Trümpy 1973, personal communication *in* Dennis and Atwater 1974, p. 1034; Alpinotype- or A-subduction of Bally 1975; also *Ver-*