The Proterozoic Ophiolite Problem, Continental Emergence, and the Venus Connection

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To account for the lack of preservation of ophiolites (fragments of oceanic crust and mantle) in old orogenic belts (age 1000 to 2500 million years), a hypothesis proposes that the magmatic oceanic crust formed during sea-floor spreading was thicker during the cited time interval. This thickening led to reduced contrast between the elevation of continental and oceanic regions and to greater average flooding of the continents. The resultant distribution of elevation may have resembled modern Venus more than modern Earth.

ALTHOUGH PLATE TECTONICS FOR present Earth is almost universally accepted, a focus of controversy is its extension into the geologic past. Direct evidence of sea-floor spreading, in the form of oceanic crust with magnetic striping, is present for only the past 200 million years (m.y.). Indirect evidence, such as rock suites similar to those formed at modern plate margins or paleomagnetic evidence of large shifts of continental rocks relative to the magnetic poles, is abundant for the time interval from 200 to 1000 million years ago (Ma), and the presence of plate tectonic processes as presently observed is accepted for this time interval. More problematic, however, is the time interval from 1000 to 2500 Ma, or of the middle and lower Proterozoic. During this time period, some features ascribed to plate tectonics are present and others are lacking.

A key plate tectonic indicator in younger orogenic belts (less than 1000 m.y. old) is the presence of ophiolite complexes (fragments of oceanic crust and mantle). These complexes are thought to represent oceanic crust formed in spreading centers in the oceans and preserved in the continents. Their absence in older orogenic belts (from 1000 to 2500 Ma) could be construed to indicate that sea-floor spreading as we know it today did not take place at that time.

This report presents a hypothesis to account for the lack of ophiolites for the time period before 1000 Ma. The hypothesis proposes that in the time interval from 1000 to 2500 Ma (middle to lower Proterozoic) sea-floor spreading did occur, but the resultant oceanic crust was thicker during this time, so that continental freeboard, or the difference of elevation between continents and ocean basins, was less. The model provides a mechanism for the relatively rapid emergence of continental shields during the late Precambrian. In addition, it suggests that the hypsographic curve (distribution of elevation) of Earth during the time interval from 1000 to 2500 Ma may have resembled that of modern Venus or Mars more closely than that of modern Earth.

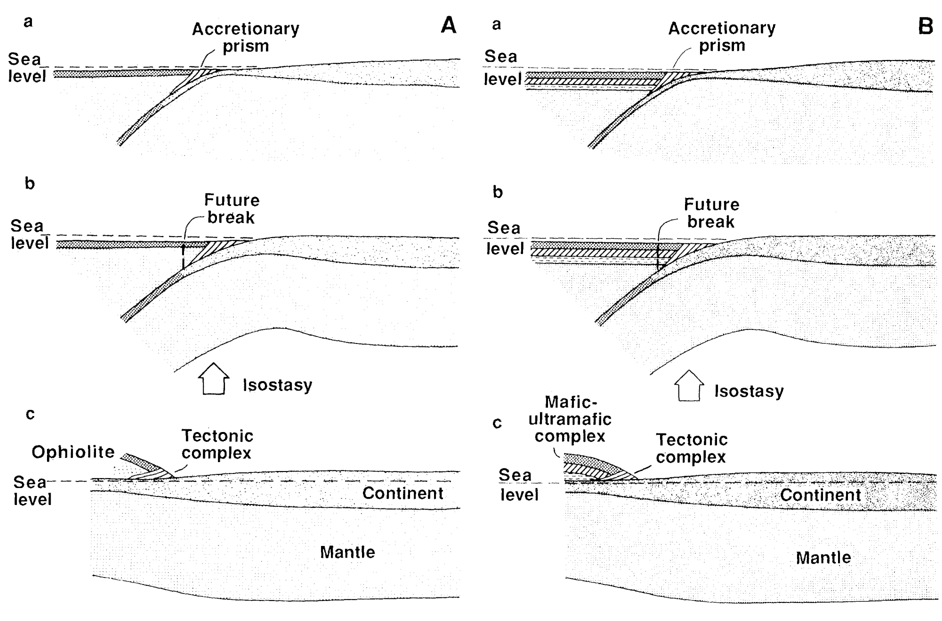

Fig. 1. Diagram of the mechanism of ophiolite emplacement. (A) Postulated mechanism of emplacement since 1000 Ma. Collision of continental margin with subduction zone (a) results in its partial subduction (b) until the buoyant effect of continental crust arrests subduction. Isostasy takes over, resulting in uplift and exposure of fragments of oceanic crust and mantle of the former overriding plate as ophiolite complex (c). Accretionary deposits become tectonic complex at the base of the ophiolite complex. Modified from Moores in (*4*). (B) Postulated mechanism of emplacement of thicker oceanic crust for the time period 1000 to 2000 Ma. Diagonal and horizontal ruled patterns depict oceanic crust two and three times modern thickness, respectively. The collisional process is the same as for (A), except that the thicker magmatic crust results in no preservation of mantle.

Ophiolite complexes are pseudostratiform sequences ideally composed, from bottom to top, of magnesium-rich tectonized (Alpine-type) peridotite, a stratiform mafic-ultramafic plutonic complex, isotropic gabbro and diorite, a mafic-silicic sheeted dike complex (formed by parallel intrusion of dikes into existing dikes), and extrusive volcanic rocks (*1*). This ideal sequence is not present in all complexes; indeed, the number of complexes that lack one or more of the units is greater than the number that possess a complete sequence (*2*). Ophiolites commonly are overlain by thinly bedded biogenic sediments of deep-sea origin, and they generally rest over continental marginal sediments along tectonic contacts [for example, (*2*)].

Despite disputes concerning the tectonic implications of their chemical composition, ophiolite complexes universally are thought to represent fragments of oceanic crust and mantle preserved within the continents. Many of these complexes, especially ones containing sheeted dike complexes, probably represent oceanic lithosphere formed at a spreading center, either in a mid-oceanic, small ocean, back arc basin, or island arc environment. The ubiquitous presence of ophiolite complexes in suture belts throughout Phanerozoic mountain systems makes them a key in the interpretation of these belts (*3*).

The mechanism of emplacement of ophiolite complexes within continents has been a subject of controversy. At present it is thought that they most likely are emplaced by the collision of subduction zones with a continental margin or island arc crust (*2, 4*) (Fig. 1A). During this process a piece of the oceanic crust and a portion of the uppermost mantle are emplaced over the continental margin as an ophiolite complex.

Relations in a number of complexes, such as the Vourinos complex, Greece (*5*), the Bay of Islands complex, Newfoundland (*6*), and perhaps the Voykar mass, Urals (*7*), suggest that a maximum total thickness, about 10 to 12 km, of ophiolite complex is

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emplaced, regardless of the thickness of the mafic portion. Presumably this maximum thickness is related to the ability of the buoyant continental margin to lift the mantle above sea level. Thicker wedges would remain submergent or be broken off by faulting.

Despite their presence in most Phanerozoic and late Precambrian suture belts, ophiolites seem to be lacking in Proterozoic mountain belts before about 1000 Ma. The oldest recorded ophiolite, the Bou Azzer complex, Morocco, has a radiometric age of 788 Ma (*8*), as well as a fully developed ophiolite sequence of serpentinized tectonite ultramafics, cumulate gabbro, and a mafic volcanic-intrusive complex. This lack of ophiolites is a key difference between belts before 1000 Ma and younger belts and hampers the direct application of Phanerozoic plate tectonic models to the older belts. Three possibilities are suggested:

1) Plate tectonics as now conceived was not operating in mid-lower Proterozoic time (1000 to 2500 Ma). Although some paleomagnetic data (*9*) support this possibility, recent developments in the geology of Proterozoic belts (*10*) suggest that continental breakup and collision occurred throughout the Proterozoic at a rate equal to or greater than that of the Phanerozoic. Most of the "petrotectonic suites" of plate tectonics are present in Proterozoic belts.

2) Ophiolites as now known are present in Proterozoic suture belts, but they have gone unrecognized; however, this possibility seems unlikely. Most of Earth's Proterozoic suture belts have been mapped at some level of detail. If ophiolites were present, they would be indicated in the geologic descriptions of these sutures (*11*). So far no ophiolites that adequately correspond to the definition above have been described. In particular, pseudostratiform sequences that present a strong contrast between tectonite mantle and stratiform mafic-ultramafic rocks do not seem to exist in suture belts older than about 1000 m.y.

3) Ophiolites are not present in Proterozoic suture belts older than 1000 m.y. Instead, their place is taken by rock sequences that resemble ophiolites but differ in significant respects from Phanerozoic examples. This seems to be the most likely possibility.

How do orogenic belts from 1000 to 2500 Ma differ from younger ones? They do exhibit suture belts with mafic and ultramafic rocks in the tectonic positions expected of ophiolites. However, these mafic-ultramafic complexes differ significantly from ophiolites because they lack the strong contrast between basal tectonite magnesium-rich ultramafic rocks and overlying stratiform plutonic mafic-ultramafic rocks. In Phanerozoic complexes, this contact is thought to represent the petrologic mantle-crust interface. In other words, the "petrologic" mantle is not preserved in Proterozoic mountain systems that existed from 1000 to 2500 Ma. The following examples emphasize this point.

The circum-Superior belt, Canada. This 2000-km belt, a 2150-Ma suture belt, separates the Archean Superior province from the Proterozoic Churchill province (*11*). The dominant lithologies along the belt include variously deformed mafic to ultramafic intrusive and extrusive rocks emplaced into or over rocks of the Superior craton. The basal contact of the mafic-ultramafic rocks is thought to be principally depositional, although the degree of metamorphism and structural complexity increases away from the Superior province rocks. The thickness of igneous and intercalated sedimentary rocks aggregates as much as 11 km. Although ultramafic plutonic rocks are reported, they all apparently represent deformed stratiform rocks, not mantle tectonites.

The Goiás mafic-ultramafic complexes, Brazil. These rocks from approximately 2000 Ma extend for 300 km along the Archean-Proterozoic contact in the central Goiás state of Brazil (*12*). The rock sequence includes peridotite and gabbro at the base, succeeded by anorthosite, and finally closely related intermediate and silicic volcanic rocks. This sequence is approximately 13 km thick. The lower mafic and ultramafic rocks exhibit granulite-facies metamorphic assemblages, whereas the upper rocks display amphibolite facies assemblages. All rocks currently are tectonites; thus no tectonite-cumulate boundary is preserved. Individual layers within the ultramafic rocks that are traceable for several kilometers suggest that these rocks originally were stratiform cumulates, rather than mantle tectonites.

The Giles complex, Western Australia. This complex consists of a variegated mass of mafic and ultramafic plutonic rocks, as much as 6.5 km thick, that grades upward into volcanic rocks as thick as 3 km (*13*). Although the basal contact is described as intrusive, the evidence reported seems compatible with the idea that the contact is in

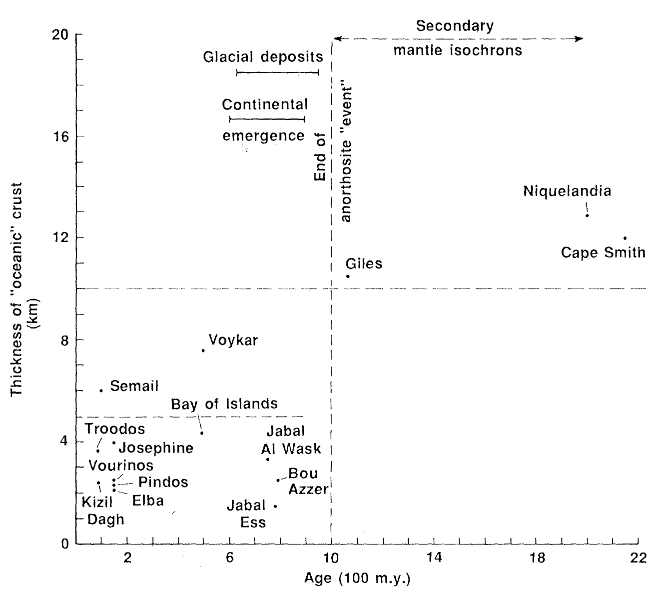

Fig. 2. Plot of thickness of mafic crust in ophiolites versus age. Sources of data: Semail, Oman; Troodos, Cyprus; Kizil Dagh, Turkey; Pindos, Greece; Elba, Italy; and Vourinos, Greece [all of the above locations in (*17*)]; Josephine, California-Oregon (*18*); Bay of Islands, Newfoundland (*6*); Jabal Al Wask and Jabal Ess, Saudi Arabia (*19*); Bou Azzer, Morocco (*8*); Voykar, Urals, U.S.S.R. (*7*); Giles, Australia (*13*); Niquelandia, Goiás, Brazil (*12*); and Cape Smith, circum-Superior, Canada (*11*). Also shown are times of increase in sediment volume (*20*), approximate end of anorthosite "event" (*22*), and late Precambrian glaciation (*21*). Dashed lines at 5 and 10 km are the average thickness of present oceanic crust and maximum thickness of emplaced ophiolites, respectively.

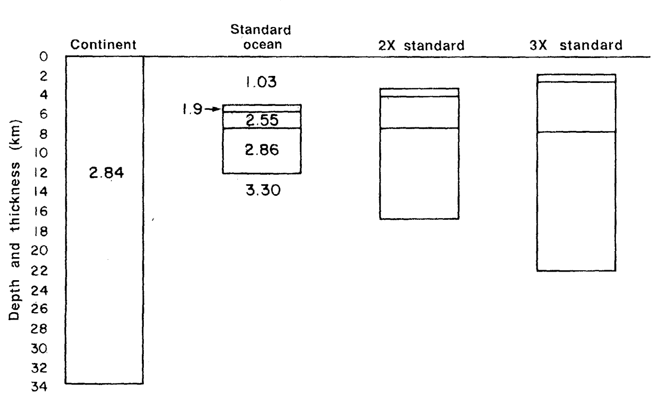

Fig. 3. Isostatic position of continental crust, modern oceanic crust, and hypothetical oceanic crust two and three times as thick as at present. Figures are average densities in grams per cubic centimeter. Densities for sections labeled "2X standard" and "3X standard" are the same as comparable layers on column labeled standard ocean. Construction based on data from (*23*).

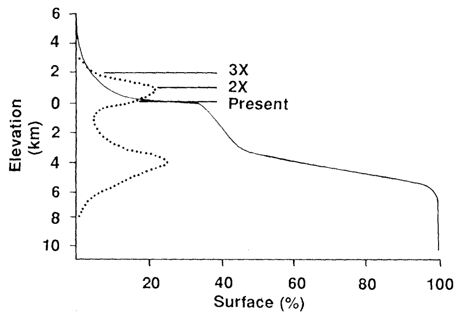

Fig. 4. Distribution of elevation on modern Earth [adapted from (*25*)]. Solid line, modern cumulative hypsographic curve. Dotted line, percentage of surface per kilometer of elevation. Curves display strongly bimodal nature of present Earth elevation distribution. Horizontal lines labeled "present," "2X," and "3X" show, respectively, present sea level and postulated level if oceanic crust were two and three times as thick as in Fig. 3. Projection of horizontal lines to intersection with solid curve indicates that approximately 90% (for 2X) and 95% (for 3X) of Earth's surface would be covered with water. Postulated change from oceanic crust two to three times as thick to present thickness thus would correspond to significant lowering of sea level.

part tectonic. A rubidium-strontium age of 1060 m.y. has been reported for the overlying volcanic rocks (*14*).

The complexes described above apparently are present in the position occupied by ophiolites in Phanerozoic suture belts. Each complex has a stratiform mafic-ultramafic intrusive complex overlain by an apparently coeval extrusive sequence. As such, each resembles the upper, magmatic, part of an ophiolite complex, except that each is much thicker. The Goiás complex is described as tectonically overlying older rocks. The presence of a tectonic contact beneath portions of the circum-Superior belt and Giles complex can only be surmised, however. On the basis of the tectonic positions of these examples, at least a partial tectonic contact appears to be likely. This conclusion is controversial as it represents second-guessing the conclusions of geologists in the field. Similar tectonic-igneous arguments on Phanerozoic ophiolites have occurred (*5, 15*), and in most cases contacts originally thought to be igneous have been reinterpreted as a complex stack of thrust sheets, some preserving primary igneous contacts (*16*). The interpretation of these apparently contradictory relations is that they preserve a sequence of paleogeographic environments ranging from platform at the bottom of the tectonic stack to oceanic at the top. Thus igneous contacts resulting from initial continental rifting are preserved toward the bottom of the thrust stack, but the uppermost contacts are tectonic. Applied to the circum-Superior and Giles complexes, this concept would mean that the igneous contacts observed along the margins or at the base of the sequences represent the initial continental rifting, but that in the structurally higher, more deformed rocks, major thrust faults exist.

Comparison of the thickness of a mafic section exposed in late Precambrian and Phanerozoic ophiolite complexes with those sections of possible older equivalents suggests that the mafic "oceanic" crust of 1000 to 2500 Ma was considerably thicker (Fig. 2) (*17–22*).

The relations outlined suggest a hypothesis that the magmatic oceanic crust was thicker during the period 1000 to 2500 Ma, perhaps owing to greater amounts of partial melting of a more fertile mantle. During the plate tectonic interactions that emplaced the oceanic crust over continental margins, not enough vertical section was lifted up to expose the suboceanic mantle (Fig. 1B). The maximum thickness observed in Phanerozoic ophiolites suggests that if the oceanic crust of 1000 to 2500 Ma were thicker than about 10 km, then the mantle would not have been preserved.

The isostatic effects of the hypothetical 10- to 13-km-thick oceanic crust would be considerable. The possible effects are shown in Fig. 3 by a comparison of the isostatic position of standard oceanic and continental crust, with hypothetical oceanic crust two or three times modern thickness (*23*). This comparison suggests that the average ocean bottom may have resided at 2 to 3 km below the average continent 1000 to 2000 Ma, rather than 5 to 6 km below as at present.

What eustatic effect would such shallower oceanic depths produce? They would result in a higher stand of sea level, but the extent would depend upon the relative area and volume of continental crust. These crust data are extremely difficult to fix with certainty, but a popular assumption is that most of the continental crust was present by 2500 Ma (*21, 24*). By using this assumption it is possible to estimate that the minimum effect would be to raise sea level approximately ~0.67 km for each 1-km rise in the level of the sea floor. For the isostatic cases illustrated in Fig. 3, the resultant rise in sea level would be 1.3 to 2 km. Superimposed on a modern hypsographic curve, the resultant sea level stands would cover 90 to 95% of Earth's surface, as indicated in Fig. 4 (*25*).

Rodgers *et al.* (*26*) suggested that after consolidation, shields undergo a period of subsidence and sedimentation lasting possibly several hundred million years, followed by crustal thickening and uplift to give rise to the present topographic level. The hypothesis presented in this report suggests that the emergence of the shields resulted

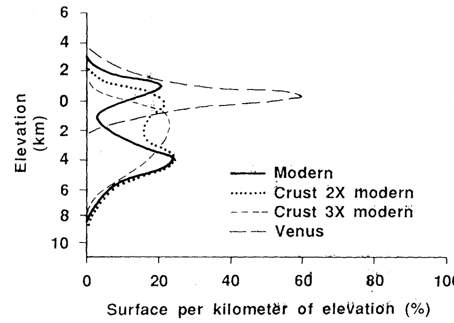

Fig. 5. Comparison of modern hypsographic curves for Earth and Venus and hypothetical curves of 1000 to 2500 Ma for Earth. Hypothetical curves for Earth are positioned to reflect increasing amounts of surface inundation, as suggested in Fig. 4. The reduced continental freeboard postulated in Fig. 3 would result in a much less strongly bimodal, or even a unimodal (3X modern), distribution of elevation on Earth, comparable to that of modern Venus.

not from their thickening but simply from draining the water off of the continents by thinning of the oceanic crust, and the resultant increase in continental freeboard and ocean basin volume. This postulated event may have caused the increase in sediment volume and continental glaciation that is thought to represent the onset of continental emergence, as argued by Hargraves (*20*).

If the ocean basins of 1000 to 2500 Ma were significantly shallower, then the distribution of elevation would have been significantly different than at present. The present sharply bimodal distribution of elevation may have been considerably blurred, with two peaks much closer to each other, or even only one broad peak, as illustrated in Fig. 5. The resultant pattern is reminiscent of the elevation distribution on Venus and possibly on Mars (*27*). Could present-day Venus or Mars be a tectonic analog for mid-Proterozoic Earth? It is easy to imagine plutonic complexes beneath martian or venerean volcanoes the size of the Proterozoic Bushveld or Great Dyke complexes in southern Africa.

A final question concerns the possible reason for the hypothetical decrease in thickness of oceanic crust. The hypothesis implies that spreading centers of 1000 to 2500 Ma produced a magmatic crust two to three times as thick as at present. One might speculate that before 1000 Ma, a greater proportion of a more fertile mantle was melted to produce the magmatic oceanic crust. The relatively rapid decrease in oceanic crustal thickness postulated to have taken place between 800 and 1000 Ma, as suggested by Fig. 2, therefore would correspond with a concurrent change from a more fertile to a more depleted mantle source. As indicated in Fig. 2, this timing also corresponds to the end of the "anorthosite event." This "event" was an episode in the history of Earth from approximately 1000 to 2000 Ma of widespread intrusion of rocks composed nearly exclusively of plagioclase feldspar, or "anorthosites." Additional evidence for this postulated change in mantle source may also be provided by its close correlation in time with the minimum age of "secondary mantle isochrons" (*22*).

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Does the Binding of Cyclosporine to Calmodulin Result in Immunosuppression?

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The cyclosporines are a family of cyclic endecapeptides that cause a profound suppression of primary immune stimulation both in vitro and in vivo. Recently, the regulatory protein calmodulin (CaM) has been implicated as a target for cyclosporin A (CsA) binding. This study utilized two less-active isomers of CsA to evaluate the specificity and biological significance of CaM binding. The three cyclosporines exhibited equivalent in vitro binding to CaM, regardless of immunosuppressive activity. Furthermore, CaM-dependent enzyme systems were inhibited equally by active and inactive cyclosporines, but only at concentrations 100 times those necessary to block lymphocyte activation. Thus the exquisite immunosuppressive stereospecificity displayed by cyclosporine isomers is not reflected in the binding to and inhibition of CaM, suggesting that inhibition of CaM-dependent processes is not sufficient to explain the immunosuppressive activity of CsA.

SYNTHETIC AND NATURALLY OCCURRING isomers of the cyclosporines exhibit a wide range of biological activity, from the strongly immunosuppressive cyclosporin A (CsA), to the weakly suppressive [Val^2]cyclosporine (CsD), to the immunologically inactive stereoisomer [(D)-*N*-methyl-Val^{11}]cyclosporine (CsH). Amino acid substitutions at or adjacent to the unique *N*-methyl-4-butenyl-4-methyl-threonine (MeBmt) at position 1 appear to have the greatest effect upon drug uptake and immunosuppressive activity (*1, 2*).

Specific defects in helper T (thymus-derived) lymphocytes treated in vitro with CsA include a blockade in transcriptional activity of at least two lymphokine genes: γ-interferon and interleukin-2 (*3, 4*). The hydrophobic CsA molecule does not interact with specific cell surface receptors but rather partitions through the plasma membrane, where it may interact with cytoplasmic target sites (*2*). Two candidates for CsA-binding proteins are calmodulin (CaM) (*5*) and an unrelated protein termed cyclophilin (*6*). Inhibition of CaM-dependent cascades during lymphocyte activation would be consistent with the central regulatory role of CaM in Ca^{2+}-mediated cellular processes (*7*).

The binding of Ca^{2+} ions by CaM results in the formation of hydrophobic domains through which CaM can bind to and regulate the activity of target proteins (*7, 8*). Lipid-soluble compounds of both synthetic and natural origin can antagonize the activity of CaM by binding to and blocking the exposed hydrophobic domain (*8*). Thus, CaM antagonists such as *N*-(6-aminohexyl)-5-chloro-1-naphthalenesulfonamide (W-7) (Sigma), trifluoperazine (TFP) (Sigma), and chlorpromazine also block the lymphoproliferative response to antigens, mitogenic lectins, or calcium ionophores without inhibiting the response to exogenous interleukin-2 (*5, 8, 9*). Analysis of the structure-function relations of synthetic CaM antagonists suggests that inhibitory activity is related to the hydrophobic index of the compound and stereospecific interactions of the ligand with its binding site (*8*). The availability of structural and stereoisomers of cyclosporine has allowed us to examine the structure-function relations between CaM binding and immunosuppressive activity.

The cyclosporines under investigation contain single amino acid replacements in the clinically useful isomer CsA (*3*). Substitution of valine for α-aminobutyric acid at position 2 yields CsD, while CsH has an L to D stereoisomerization of methylvaline at position 11. The immunosuppressive activities of the three cyclosporine isomers were profoundly affected by the single amino acid substitutions, as demonstrated by their relative abilities to block lymphoproliferation of murine spleen cells in response to the mitogenic lectin concanavalin A (Con A) (Fig. 1). The dissociation constant (binding affinity) (K_d) for CsA "binding" to lymphocytes and the dose of CsA yielding a 50% suppression of mitogen-induced lymphoprolifera-

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