is consistent with a depth of 15 km. The wide area of macroseismic reports is also qualitatively consistent with a moderately deep crustal as opposed to a near surface focus.

Fig. 2 locates earthquakes since 1900 over intensity V in the north of England from the International Seismological Summary (ISS) and also events of similar intensity taken from the annual reports of the British Association for the Advancement of Science 1900–63 (Section A: Seismological Investigations). Most of these events lie around the edge of the Pennine block and to the south of the present event. Exceptions are the 1911 Grasmere event and the 1901 Carlisle event. Davison[6] catalogues a series of nineteenth century earthquakes in the Carlisle, Grasmere and Kendal areas close to the 1970 event. The only earthquake in the ISS in the immediate vicinity of the 1970 event is the Wensleydale event of January 14, 1933. This was studied by Rowland of the Stonyhurst College Observatory and was discussed in an unpublished report presented to the British Association in 1933. Rowland calculated the position of the epicentre using *P–S* time separation on the records obtained at Stonyhurst, Durham and Bidston. From the relative arrival times of the phases he concluded that the depth of focus was ". . . greater than normal. In determining the epicentre from the three nearest stations it was found impossible to obtain intersecting circles by adopting velocities appropriate to *Pg* and *Sg* but good concordance was obtained by taking those of P^* and S^*". By this statement we infer that he meant that the earthquake was not a near surface event and occurred fairly deep in the crust.

Fig. 3 (from Bott[7]) places the 1970 event in its geological background. The epicentre lies near to the junction of the Pennine and Dent faults and the Stainmore Trough. The focus is at a depth of approximately 15 km and is to be associated with the downward continuation of the surface structural features of the western edge of the North Pennine block.

We thank Mr E. Tillotson for bringing the work of the Rev. J. P. Rowland to our notice and for advice on previous events in the area, Dr R. Lilwall for help in computing, Mr G. Neilson for assistance in collating the data and Mr P. D. Marshall for his advice and encouragement.

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Ultramafics and Orogeny, with Models of the US Cordillera and the Tethys

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An attempt to synthesize regional and structural geology, particularly in the Alpine and Cordilleran systems, during the whole of Phanerozoic time.

THE emplacement of ultramafic rocks in mountain systems provokes a number of interesting and important questions. Hess[1,2] pointed to the existence of belts of these rocks and showed that they were apparently intruded in the initial stages of orogeny. Tethyan occurrences of the ophiolite suite[3,4] may be fragments of oceanic crust and mantle and there is a similar occurrence in Papua[5]. Temple and Zimmerman have recently proposed[6] that emplacement of such oceanic crustal and mantle rocks may be achieved by collision of continental margin with a subduction zone, or lithosphere consumption (Benioff) zone, dipping away from the continent rather than towards it as is more common (see Fig. 1).

This article carries the hypothesis further, applying it to a preliminary analysis of the Alpine and Cordilleran systems. The underlying assumptions in this analysis include: (1) most large ultramafic–mafic sheets represent oceanic crust and mantle[3,4,7–9]; (2) the emplacement of large ultramafic sheets represents the collision of a continent with a subduction zone dipping away from the continental margin (Fig. 1); and (3) an island arc will migrate outward towards its trench[10] so that there will be high heat flow behind the arc as in the Marianas and Tonga–Kermadec arcs[11] and the Japan Arc[12,13].

After such a collision, the buoyancy of the continental material will arrest the process of continental subduction

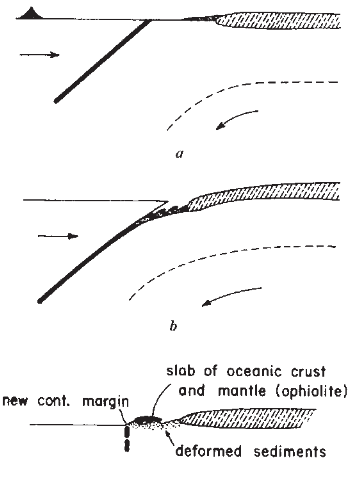

Fig. 1. Schematic diagram of ophiolite emplacement, modified after ref. 6. Diagonal pattern, continent; stippled, marginal sediment; horizontal lines, island arc; heavy lines, subduction zone; dashed line, lithosphere–asthenosphere boundary; arrows, relative motions. *a*, Situation just before collision; *b*, at collision; *c*, after collision. *c* shows a new continental margin developed oceanward of the deformed sediments and a new slab of oceanic crust and mantle now incorporated on the continental margin.

and the final product will look perhaps as in Fig. 1c. There may be some accretion by the addition of deformed sediments and a slab of oceanic crust and mantle to the continent, but the details of this process will vary from one occurrence to another. One possibility is that the direction of subduction "flips" and the zone continues operation dipping under the continent[6,14]. The important feature of the process, however, will be the asymmetric deformation of the old continental marginal material and basement away from the ocean and towards the foreland. The marginal material will be affected only when it first intersects the subduction zone so that this collision might be called the "intrusion" of ultramafics ". . . during the first great deformation of a mountain belt" (ref. 1, p. 391).

Hess[1] also observed that the age of emplacement of ultramafics, hence the beginnings of orogeny, migrated in time along the strike of a mountain belt. In my model, this migration in time can be seen as a migration of the point of continent–subduction zone collision along the continental margin (Fig. 2). The direction of migration of the collision will depend on the orientation of the subduction zone with respect to the continental margin, as shown in Fig. 2.

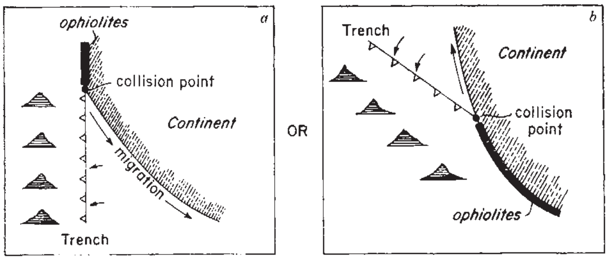

Fig. 2. Model for progression of orogeny along strike in time as migration of collision of continental margin and subduction zone as shown in Fig. 1. Arrows show relative motions. Diagonal ruled, continental margin. Barbs on upper plate of subduction zone. Small arrows indicate underthrusting plate. Horizontal rule, island arc over subduction zone.

By analysing the positions and ages of emplacement of old slices of oceanic mantle and crust exposed in mountain systems, one can establish not only the direction of dip of fossil subduction zones, but also their attitudes and migrations with respect to old continental margins. Petrological and mineralogical studies of such old ocean-mantle thrust sheets and associated metamorphic rocks afford a means of determining the thickness of the overthrust mantle–crust wedge at a given point and possibly the palaeo-geothermal gradients. The distance from this point to the toe of the wedge should provide the dip on the fossil subduction zone.

Types of Intersection

Two types of collisions between a continental margin and an oceanic subduction zone may take place in which ultramafic material will be emplaced on the continent or the margin of the continent. These collisions differ according to whether the edge of the continent was an Andes-style or Atlantic-style margin (see Fig, 3). In each case, however, the colliding subduction zone must dip away from the continental margin. This situation is relatively unusual for present island arc systems and can be seen only in the Indonesia–Australia area where the Australian plate is at present moving into the Java–New Hebrides Trench System[15]. Such a situation may have existed in New Guinea and New Caledonia in the Tertiary in which ultramafic–mafic mantle and ocean crust wedges were thrust south-west over the margin of the Australian plate[5,16]. A situation resembling Fig. 3b may be represented today by the North Arm of Celebes and Halmahera where two seismic zones dipping away from one another are nearly intersecting[15].

Whether the collision was of a trailing (or Atlantic-style; Fig. 3a) or leading (Andes-style; Fig. 3b) continental edge may be deduced from the pre-collision history of the area in question. Examples of this situation might include: (1) the Bay of Islands Complex, Newfoundland, which sits between the Canadian shield and the principal orogenic belt of Newfoundland[17] (under this model, it would have been emplaced by a subduction zone–continental collision as in Fig. 3a); (2) the Troodos Complex, Cyprus and Vourinos Complex, Greece[3], which under this model would represent the collision of a subduction zone and the African continent or a microcontinent as in Fig. 3a; (3) the Canyon Mountain Complex, Oregon[18], and the Coast Range ultramafic sheet, California[9], which would represent collisions as in Fig. 3b.

Cordillera System of West–Central United States

The western North American margin is characterized by an orogenic belt, which has as two principal features a "eugeosyncline" and "miogeosyncline" which received deposits during much of the Palaeozoic and early Mesozoic[19–21]. The width of the orogen is anomalously great in the region of the central United States. This "eugeosynclinal–miogeosynclinal" system has been affected three times by major "orogeny": by the Devonian Antler orogeny, the Permian Sonoma orogeny and the Jurassic Nevadan orogeny.

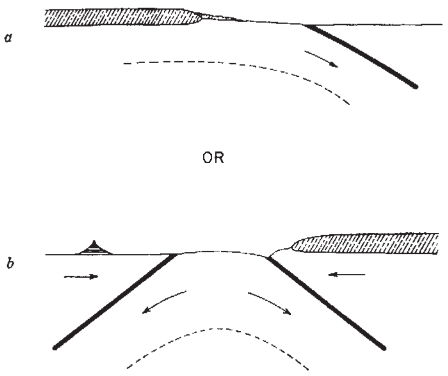

Fig. 3. Schematic diagrams of (a) trailing (Atlantic-type) marginal, and (b) leading (Andes-type) marginal collisions which may give rise to ultramafic emplacement. In b, possibly the island arc zone on the left is more vigorous than the continental marginal zone on the right and overrides it. Possible examples: a, Ordovician Appalachian–Caledonide system, Mesozoic Mediterranean–Tethyan system; b, North American Cordillera. Symbols as in Fig. 1.

All of these "orogenies" have resulted in thrusts and overturned folds directed towards the foreland[19–21]. This alternation of "eugeosynclinal–miogeosynclinal" conditions with orogeny conflicts with the interpretation that the Palaeozoic Cordillera is a simple Andean-type continental margin[22,23], and has prompted Roberts[19–21], among others, to propose a cyclic history driven by sedimentation and mantle phase changes. Much of Roberts's evidence is drawn from Nevada. In California to the west, the Sierra Nevada and Klamath Mountain basement rocks consist of lower Palaeozoic chert, clastic sediments and volcanics of the Shoo Fly and Calaveras sequences[24,25] (and E. M. M. and W. S. Wise, in preparation) succeeded by a Mississippian–Permian volcanic sequence, and a Triassic–Jurassic volcanic–sedimentary sequence. Several large ultramafic masses are also exposed in the Klamaths and Sierra Nevada. The 400 square mile Trinity ultramafic pluton of the Klamath Mountains[26] is pre-Permian and probably Devonian in age[27]. The large Feather River peridotite mass in the northern Sierra is probably pre-

Triassic[24,25] (and E. M. M. and W. S. Wise, in preparation), as is the Canyon Mountain Complex in Oregon[18].

In the California–Oregon Coast Ranges, the Franciscan mélange and associated material probably represent the result of late Mesozoic–early Tertiary underthrusting of the Pacific plate under North America[22]. The Great Valley sequence may be deposited on Jurassic oceanic crust[9,28]. Most late Mesozoic structures of the western Sierra and Coast Ranges are overturned to the west. This westward overturning to the west, coupled with eastward overturning to the east, has prompted Burchfiel and Davis[29] to call attention to the "two-sided" nature of the Cordilleran orogen.

I suggest that all these diverse and apparently conflicting features of the Cordilleran orogen can be fitted into a model in which a North American continent with a Japan-style or Andes-style margin[30] has collided three times in Phanerozoic time with a subduction zone dipping the other way, representing possibly a collision as in Fig. 3*b*. The Japan or Andes-style continental margin is reflected in the "eugeosynclinal–miogeosynclinal" suite, and the intersections are represented by large ultramafic–mafic masses and the eastward directed orogenies.

The lower Palaeozoic Cordilleran system of west-central United States reflects a Japan Sea-type continental margin (Fig. 4*a*). A carbonate platform and trough (shelf and miogeosyncline) passed westward into a lower Palaeozoic foredeep clastic basin of Japan Sea-type (the Vinini Formation) and a volcanic arc (the Valmy Formation) in western Nevada[19–21]. The Shoo Fly and Calaveras

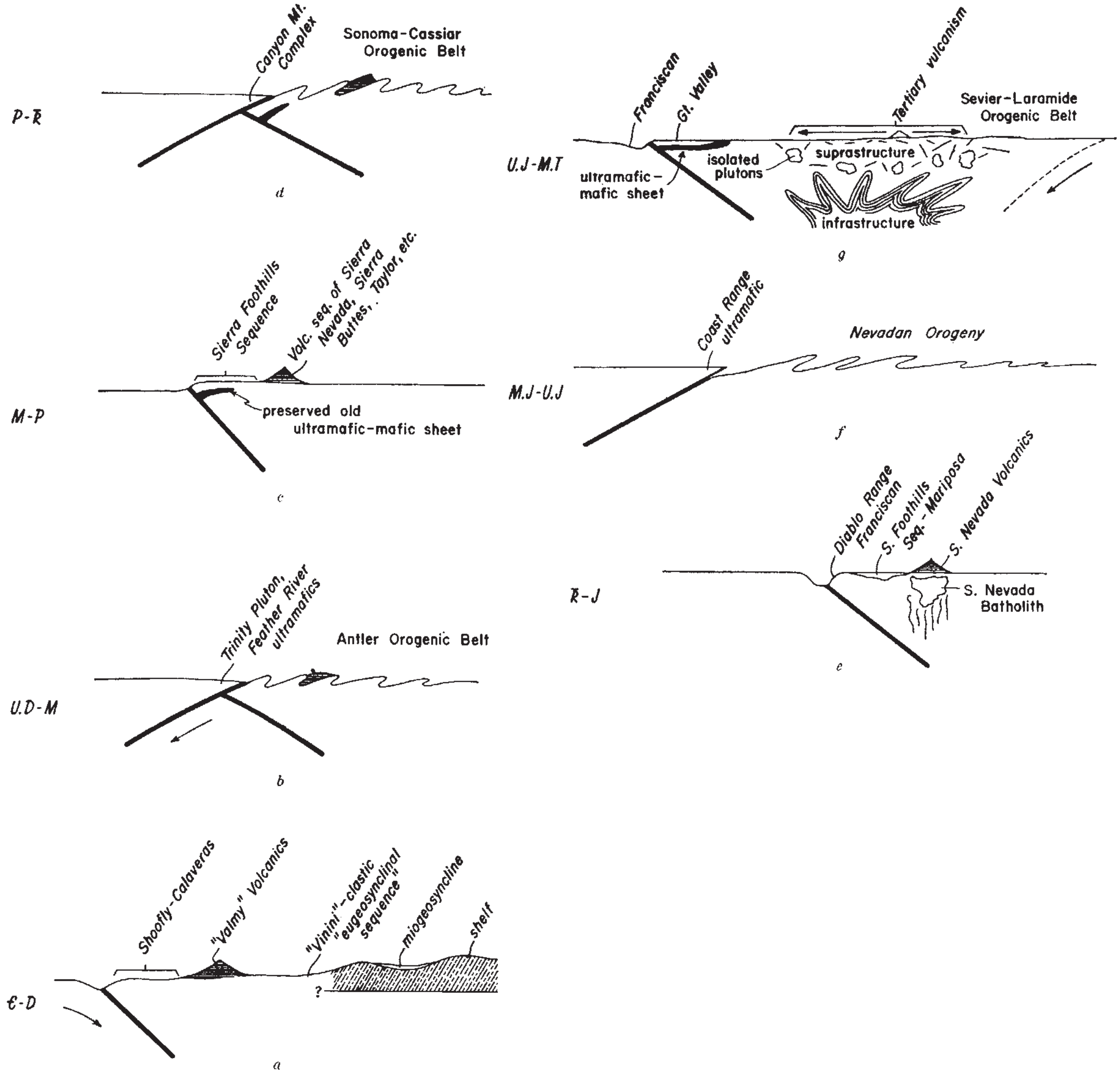

Fig. 4. Model for evolution of western US Cordillera. Heavy line, subduction zone; diagonal ruled area, continent. *a*, (E–D) Model for development of margin from middle Cambrian to Ordovician and possibly to Devonian. "Miogeosyncline" is thick carbonate deposits in eastern Nevada. "Vinini-Valmy" are "eugeosynclinal" deposits in western Nevada. "Shoofly-Calaveras" are chert, clastics, and associated sediments and volcanics of northern Sierra Nevada[19–21,24–26]. *b*, (U.D.–M.) Postulated collision of subduction zone in upper Devonian-Mississippian time, emplacing Trinity ultramafic pluton of Klamath Mountains[27,28] and causing Antler orogeny[19–21]. *c*, (M–P) Andean-type continental margin operative during Mississippian through Permian time. Sierra foothills sequence of chaotically deformed Palaeozoic rocks with lens-like bodies of mafic and ultramafic rocks[40]. *d*, Collision of subduction zone system which produced Sonoma-Cassiar orogeny and emplaced the Canyon Mountain complex of Oregon[18,32,33]. *e*, Triassic–lower Jurassic Andean-type continental margin[19–26]. Diablo Range Franciscan is a thick sequence of deformed and metamorphosed greywacke, chert, volcanics, and ultramafics. Sierra foothills sequence is same as in *c*. *f*, (M.J.–U.J.) Postulated collision of subduction zone and continental margin resulting in Nevadan orogeny. Coast Range ultramafic is ultramafic–mafic sheet below Great Valley sequence[9,29]. *g*, (U.J.–M.T.) Inferred development of western Cordillera subsequent to Nevadan orogeny. Subduction zone on left resulted in Franciscan–Great Valley relations[22,28], underthrusting to right produced Sevier–Laramide thrust belt and Outer Rockies[19–21,36,37,45], area between experienced formation of infrastructure of recumbently folded metamorphic rocks and suprastructure of low-angle normal faulting and isolated plutons[35–40] and, in early Tertiary, volcanism[41–43].

sequences of the Sierra Nevada may represent trench or oceanic material. A collision of this continental margin with a subduction zone dipping away from it in late Devonian–early Mississippian time possibly emplaced the Trinity and the Feather River ultramafic bodies and resulted in deformation of the pre-existing continental marginal rocks in the Antler Orogeny (see Fig. 4*b*). These ultramafic bodies may have been emplaced up over pre-existing volcanic and sedimentary rocks.

After this collision a subduction zone dipping under North America resumed operation, with a shift oceanward of the locus of volcanism (Fig. 4*c*). This period of activity is reflected in the upper Palaeozoic volcanogenic deposits located in the Klamath Mountains, Sierra Nevada and western Nevada.

Another possible collision of a subduction zone with the continental margin in the Permo–Triassic emplaced an ultramafic sheet now represented by the Canyon Mountain Complex, Oregon[18,31,32], and possibly the Feather River body. The resulting deformation of continental marginal rocks is the Sonoma Orogeny in Nevada (which is probably equivalent to the Cassiar Orogeny in British Columbia; Fig. 4*d*).

During the Triassic and lower Jurassic, a subduction zone again operated under North America (Fig. 4*e*). Volcanic and plutonic rocks of this age are found in the Sierra Nevada, the Klamath Mountains and in western Nevada. Trench material for this episode may be represented by the chaotic western Palaeozoic–Mesozoic belts of the Klamath Mountains and the old Franciscan rocks of the eastern Coast Ranges[9,22,23].

In the late middle Jurassic another collision occurred between the North American continental margin and a subduction zone dipping away from it, which may have emplaced the Colebrook Schist in Oregon[33], the glaucophane schist–eclogite terrane of the California Coast Ranges[34] and the Coast Range peridotite sheet[9,28]. This collision deformed the Andean-type margin of North America, and is traditionally called the Nevadan orogeny (Fig. 4*f*).

From the late Jurassic to Miocene, a subduction zone dipping under the western margin of the continent continued activity[22,23], but in the early middle Cretaceous, possibly as a result of beginning of rapid drift in the Atlantic Ocean, a zone of west-dipping subduction may have developed in eastern Nevada and western Utah (Fig. 4*g*). This zone resulted in underthrusting of the eastern foreland and gave rise to the Sevier–Laramide overthrust belt[35,36] and the outer Rockies[19–21]. The area in between western Nevada and central Utah thus became a zone between two oppositely dipping subduction zones (Fig. 4*g*), and, hence, possibly a zone of formation of infrastructure, Jurassic to Miocene plutonism and metamorphism, and low-angle normal faulting of the suprastructure[37–39]. Cessation of the west dipping zone in the Eocene may have caused the east dipping zone to extend under central Colorado as proposed by Lipman and others[40–42], causing volcanism in the San Juan Mountains and Great Basin.

The last effect of the foreland underthrusting was formation of the Wyoming and Colorado Rockies in the late Cretaceous–early Eocene. These dome and wedge uplifts of shield and overlying shelf rocks may represent buckle folds of the continental crust. (Assuming equal viscosities, the dominant wavelength of a fold approaches 3·46 times the thickness of the folding layer[43]. Calculations of the folding layer thickness based on this assumption yield values of 20 km just east of the Laramide thrust front to 46 km for the crust between the Bighorn Mountains and the Black Hills[44]. These values seem plausible thicknesses of continental crust at the time and locations in question.) Late Miocene to Pliocene activity has been in response to a new situation related perhaps to the collision of the East Pacific Rise with North America and the reorientation of spreading in the past 10 m.y.[40–42,45–47]. Isostatic rebound subsequent to termination of subduction possibly gave rise to the Plio–Pleistocene uplift of the Basin and Range and Colorado Plateau provinces.

Correlation with Other Cordilleran Structures

Clearly, the picture I have presented will vary considerably along strike from the cross-section chosen. In particular, the two postulated late Mesozoic–early Tertiary opposing subduction zones come together in the Idaho Batholith region, and possibly also in the Mojave Desert region of eastern California[48]. In each of these areas one would expect to find a great deal of thermal (batholithic) activity connected with divergent structures. In southeastern California, Burchfiel and Davis[48] describe two major divergent thrust zones separated by a 50 mile wide central terrane of abundantly intruded sediments unaffected by the divergent structure (*Zwischengebirge*). This *Zwischengebirge* may be equivalent to the entire Basin and Range province, and represents an area where the two postulated opposing zones are nearly intersecting.

The Alpine System

In the Alps proper, the Mesozoic Tethyan sequence usually developed on Hercynian basement and it consists of Permo–Triassic Verrucano red beds and volcanics, Triassic reef complexes, Jurassic–lower Cretaceous deep sea deposits and ophiolites, and Cretaceous carbonates and clastic sediments[49]. This stratigraphic–tectonic sequence can be interpreted as a Triassic opening of a Tethyan seaway in the western Alpine region, foundering of the continental margin areas in late Triassic (formation of large reef complexes), deep sea sedimentation during the Jurassic and lower Cretaceous, followed by closing of the ocean (emplacement of ophiolites) commencing in the upper Jurassic in the west and proceeding eastward in time.

The spatial relations of ophiolites in the Tethyan systems suggests the intersection at various places along strike of both the African and Eurasian continents with subduction zones dipping away from the margins, as shown in Fig. 5.

Fig. 5*b*, which is very simplified, shows both zones colliding at the same time and in the same position along strike of the deformed belt which are not necessarily true. Furthermore, the ridge may continue to operate during this collision. But whether or not a collision takes place, if subduction continues on zones dipping towards each other, the intervening area will become a zone of high heat flow, volcanism, sedimentation and possibly formation of infrastructure (Fig. 5*b*). This would result in a *Zwischengebirge* such as the Hungarian Basin[50–52]. Presence of a microcontinent between the two subduction zones, as perhaps the Rhodope massif in Bulgaria and Greece, and the Menderes massif in Turkey, would result in their remobilization and infrastructure formation[53].

If these conditions are developed and the continents continue to approach and finally collide and/or override each other, the result would be the "regurgitation" of the mobilized material between the subduction zones (Fig. 5*c*), and overthrusting of this crystalline material over the continents, for example, the formation and emplacement of the Penninic and the Pelagonian Nappes.

Implications for Orogeny

Several important implications for orogeny are corollary.

(1) Batholithic activity, infrastructure formation and development of characteristic early isoclinal recumbent folds are related to operation of a subduction zone[22,23]. Ophiolite emplacement and nappe formation may be related to the attempted subduction of a continent, a continent–continent or a continent–island arc collision.

(2) In the US Cordilleran system, the repeated orogenic episodes and ultramafic emplacement may have consist-

ently resulted from collision of subduction zones with the Pacific margin of North America[10]. Two sources for these zones can be suggested: (*a*) Island arc systems may be generated off Asia and migrate across the Pacific, ultimately colliding with the American margin[7]. Such a situation may be implied by Karig's[11] documentation of new crust now being formed in the seas behind the Tonga–Kermedec and Marianas arcs. He suggests that possibly all island–arc systems in the western Pacific are migrating away from Asia. (*b*) A new ridge system might develop in the Pacific or the Pacific basin might begin to close rapidly, thus causing new subduction zones to be formed somewhat marginal to and facing toward both the North American and Asian continents. These new zones would collide with the continental margins of each continent. Remnants of such a system may be represented by the west-facing arcs observed in the south-western Pacific, for example, west of Luzon and Halmahera[15], and by Tertiary emplacement of oceanic crust and mantle slabs in New Guinea[5] and New Caledonia[16].

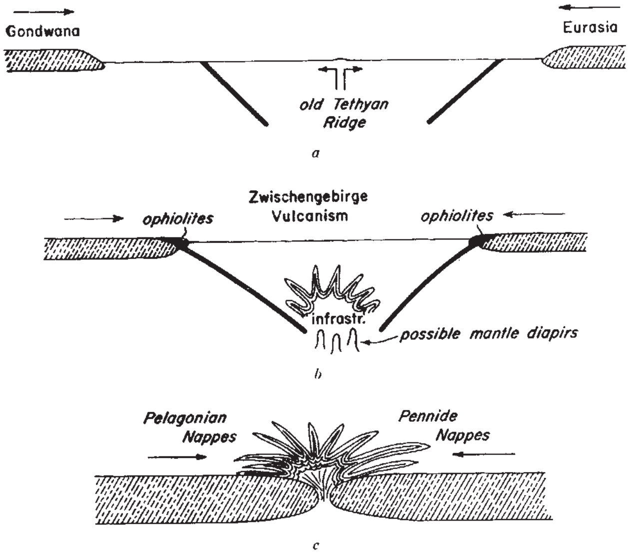

Fig. 5. Model for evolution of some Alpine features. *a*, Closing of an old Tethyan ocean basin would necessitate formation of subduction zones being placed as shown. Remnants of old Tethyan ridge may be represented by ophiolites, such as in Greece and Cyprus[3,4]. *b*, Continued subduction after emplacement of ophiolites on zones dipping in a similar manner would give rise to divergent deformed belts, separated by a *Zwischengebirge* in which infrastructure formation and volcanism would proceed, as also seen in Fig. 4*g*. *c*, Collision of continental masses would result in squeezing out volcanic material and hot infrastructure as overthrust crystalline nappes over the former Gondwana or Eurasian continent. The Penninic nappes would have come over the latter, the Pelagonian zone nappes over the former.

An important control on which system has operated may be obtained by observation of the old sheets of oceanic crust and mantle. Any evidence of an old island arc should be present in the geologic record as thick andesite accumulations over a peridotite slab. If, however, the "ophiolites" demonstrably contain only oceanic crust and mantle formed by spreading as in Cyprus and possibly Greece[3,4], then the subduction zone which emplaced them onto the continent should have been developed near the continental margin, so that not enough underthrusting would have taken place to give rise to island arc volcanism over the pre-existing oceanic crust (F. J. Vine and E. M. M., in preparation).

(3) Alpine ultramafic rocks in orogenic belts can now be differentiated into several types of occurrences: (*a*) Preserved overthrust masses of oceanic crust and mantle, for example, Vourinos–Pindos masses, Greece[3,4]; Klamath Mountains mass and Coast Range sheet, California[9,26,28]; Canyon Mountain complex, Oregon[18]; and Bay of Islands complex, Newfoundland[17]. (*b*) Disrupted parts of overthrust mantle sheets presently incorporated into mélanges, as in Italy[54], Turkey[55], California Coast Ranges[56,57] and Arosa schuppen zone[58]. (*c*) Small conformable masses of ultramafic and mafic rock in metamorphic belts, as in the Sierra Nevada and Klamath Mountains[24,25,59]; Penninic zone of the Alps[60,61]; Caledonian core region[62]; and southern Appalachians[1,2]. These masses represent either mantle diapirs emplaced in the high temperature region of *Zwischengebirge* infrastructure (Fig. 5*b*), or metamorphosed mélange sequences. (*d*) Hot diapiric intrusions with metamorphic aureoles intruded into greenschist terranes, for example, Mt Albert, Quebec[63]; Tinaquillo, Venezuela[64,65]; and Lizard, Cornwall[66]. These masses remain a problem. They may represent diapirs somehow peripheral to the subduction process, but most of these masses are bordered by a fault, and they may represent fragments of a fossil mantle overthrust sheet.

(4) All orogenic belts in the Eurasian–North American region such as the Urals, Caledonide–Taconic, Appalachian–Hercynian, seem to have resulted from the separation and subsequent collision of two continental plates, whereas the Cordilleran deformation as shown here seems to have always been the result of collision of a continent and an island arc system[7]. These relations argue for a fundamental difference between the circum-Pacific region and the Laurasia–Gondwana system during Phanerozoic time. The Pacific may be a permanent feature, which has generated within it ridges and island arcs which migrate and ultimately intersect the surrounding continental margins[67,68]. Some accretion takes place on these margins as a result of subduction zone operation (as in Fig. 4*a*, *c* and *e*), which may be more or less counterbalanced by the shortening resulting from collision of opposing subduction zones (as in Fig. 4*b*, *d* and *f*). At any rate, the evidence from mountain systems strongly implies the action of observed plate tectonic processes—sea-floor spreading and subduction—at least since the Cambrian or Ordovician.

(5) Today, on the west coast of North America, the East Pacific Rise can be seen intersecting with a trench system, which is resulting in right lateral transform fault movement[45–47]. Possibly the North American subduction zone collisions inferred above for the Devonian, Permian and Jurassic periods alternated in some cases with ridge intersections in intervening times. If relative motions between the North American plate and Pacific plate were favourably orientated during these hypothetical collisions, they may have resulted in transform fault movement. Hence the model of sequence of events in the record of the Cordillera should possibly be modified as follows: continental margin subduction system—ridge collision and transform faulting—island arc collision (orogeny)—continental margin subduction system. Thus possibly there should be evidence in the geologic record of three large scale strike-slip displacements, during the Siluro–Devonian, Permian and Jurassic. The 40 miles of pre-Mesozoic displacement on the Tintina trench[69] may be a result of this sort of process. Such recurrent strike-slip movement may also explain partly the Salinian Block emplacement[19–21], possible strike-slip movement on the Texas Lineament[70] and the truncation of Palaeozoic sedimentary trends against the continental margin[19–21] (and personal communication from B. C. Burchfiel).

(6) Where the last postulated arc to migrate toward the Pacific margin of the Americas collided with a continental mass, the result was orogeny, as in North and South America. Where no continent was present, they simply kept going, giving the Scotia and Antillean arcs, as diagrammatically represented in Fig. 6 (ref. 71). If at the same time the distance between North America and South America decreased, the result would be the Venezuelan Coast Ranges and the greater Antilles, with combined crustal shortening and strike-slip movement occurring more or less simultaneously. As this shortening continued,

perhaps the old transform faults (which would have been north of Cuba and in the Venezuelan Coast Ranges) may have been abandoned and the Bartlett Fault would have formed. One implication of this interpretation is that the northern front of this Caribbean plate is the north coasts of Cuba and Hispaniola. Hence the Gulf of Mexico represents ocean between the northern margin of the Caribbean plate and the North American continent. The Gulf therefore is at least as old as the Jurassic. If one accepts Bullard *et al.*'s[72] fit of the Atlantic Ocean and the idea that the Hercynian–Appalachian System represents a suturing of a proto-Laurasia and proto-Gondwana[73], then the Gulf of Mexico may be a remnant of Palaeozoic ocean.

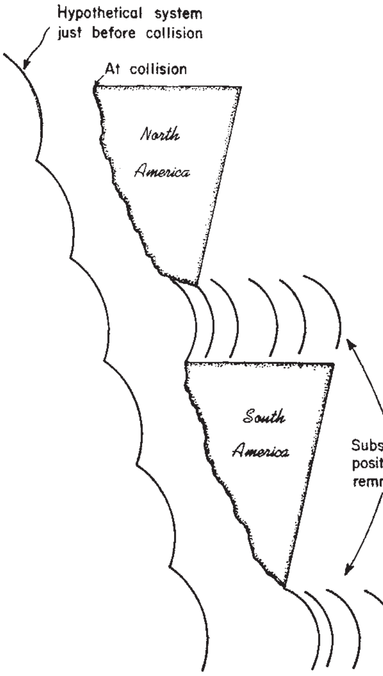

Fig. 6. Model for evolution of Caribbean and Scotia Arcs. Hypothetical island arc system collided with North and South America in Jurassic–Cretaceous time resulting in Nevadan orogeny. Where no continent was present (as between North and South America and south of South America), the remnants of this island arc system simply continued migration, forming the Caribbean and Scotian Seas. Simultaneous convergence of North and South America would result in Greater Antilles and Venezuelan Coast Ranges.

(7) During the early Palaeozoic, the margin of North America seems to have been a Japan Sea-type of continental margin, and for the rest of the Phanerozoic has been Andean-type. Nelson and Temple's model[10] for east flowing mantle mainstream convection holds that Japan Sea-type margins occur on the east sides of continents and Andean-type margins on their west sides. Does the change in margin type in the mid-Palaeozoic for North America signal a 180° change in its orientation relative to an east-flowing convection system? Correlation of such marginal types in the past with palaeomagnetic data should provide an important test of the mainstream model[7].

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