# GRAVITY TECTONICS IN THE NW DOLOMITES (NORTH ITALY)

G. B. ENGELEN

Dit proefschrift is tevens de 13e aflevering van de

GEOLOGICA ULTRAIECTINA

(Mededelingen van het Geologisch Instituut der Rijksuniversiteit te Utrecht)

This thesis is published as no. 13 of the series

GEOLOGICA ULTRAIECTINA

(Publications of the "Geologisch Instituut" of the Utrecht State University)

# STELLINGEN

1. De tectonische bouw van de Dolomieten in N. Italië kan niet verklaard worden door regionale, tangentiele compressie in de aardkost tijdens de alpiene orogenese.

2. De wervelstructuren („Schlingen") in de kristallijne gesteenten ten noorden en noordwesten van het Tonale-Judicaria-Pusteria breuksysteem kunnen gevormd zijn tijdens de (eerste fasen van de) opheffing van de oostalpiene geanticlinaal ten gevolge van de rekspanningen door differentiele verticale bewegingen.

   Carey, S. W. (1962): Folding: Journ. Alberta Soc. of Petr. Geol., Vol. 10, 3.

3. De dislocaties in de Dolomieten die als vulcano-tectonische verschijnselen van triadische ouderdom zijn verklaard, blijken tijdens het Kaenozoicum gevormde laterale diapieren in de dalwanden te zijn.

   Leonardi, P. (1953): Nuova interpretazione della tettonica della Val di Fassa e scoperta di tronchi silicizatti giuresi nella Valle del Piave: La ricerca scientifica, 23, N. 8, pp. 1399–1406.

4. De „Bermuda rise" kan beschouwd worden als een korstbuil (blaar), welke ontstond doordat materiaal van de mantel is overgegaan van een hoge-druk naar een lage-druk modificatie toen de westwaartse beweging van Noord-Amerika een drukverlaging teweeg bracht.

   Heezen et al. (1959): The floors of the oceans, I. Spec. Paper 65, Geol. Soc. of America.

5. Er kunnen twee typen submariene canyons worden onderscheiden:
   a) canyons, die wèl aansluiten op de hydrografie van het huidige land;
   b) canyons, die niet aansluiten op de hydrografie van het huidige land en voornamelijk in de continentale helling zijn ingesneden.

   Beide typen zijn het gevolg van fluviatiele erosie tijdens een periode van opheffing van de continenten in het Tertiair. Type b vormt met een min of meer regelmatig patroon de afwatering van de door stijgingsregens besproeide continentale hellingen.

6. De typische meanderontwikkeling van de middenloop van de Moezel is bepaald door een kaenozoisch horst-en-slenk systeem in NW–ZO richting, dwars op de stroomrichting.

7. De tertiaire dalopvullingen in de zuidelijke Eifel („Vallendarer Schotter") kunnen maximaal een dikte van 50 m bereikt hebben. De door Louis voor deze afzettingen afgeleide dikte van 200 m is onjuist omdat daarbij geen rekening is gehouden met jong-kaenozoische tectoniek.

   Louis, N. (1953): Über die ältere Formentwicklung im Rheinischen Schiefergebirge, insbesondere im Moselgebiet. Münchner Geogr. Hefte, 2.

8. De begrippen grote en kleine schaal uit de kartografie sluiten niet aan bij het normale taalgebruik van deze begrippen. Om verwarring te voorkomen verdient het aanbeveling om bij vergelijking van kaarten met verschillende schalen te spreken van grotere en kleinere schaalverhoudingen.

9. De planconvexe lensstructuren in de amfibolietlagen aan de Rognakust (Noorwegen) zijn waarschijnlijk tijdens de metamorfose bewaard gebleven sedimentaire structuren. Uitgaande van deze veronderstelling kan op grond van de oriëntatie van deze structuren aangenomen worden dat men hier te doen heeft met isoclinale plooien in deze gneisserie.

10. De vorming van ineengeschakelde terrassen van grote rivieren in die gebieden, die in het Pleistoceen onder periglaciale omstandigheden verkeerden, kan worden verklaard uit de afname van puinleveranties aan de rivieren ten gevolge van de puinvangende (puinvastleggende) werking van brede terrasvlakten langs de afwateringsbanen.

11. De fysiologische uitdroging van het organisme die optreedt als in poolstreken alleen sneeuwwater beschikbaar is, b.v. voor bemanningen van verongelukte vliegtuigen, is een gevolg van het geringe gehalte aan zouten in sneeuwwater.

    Rogers, T. A. (1962): Federation Proceedings 21, 224c.

12. Het verdient aanbeveling het onderwijs aan sociaal geografen uit te breiden met een cursus in de interpretatie van luchtfoto's.

13. Tegenkoppeling is geen levenskenmerk, zoals verondersteld door Bok, daar deze ook voorkomt in de levenloze natuur, zonder daarin door menselijk toedoen te zijn aangebracht.

    Bok, S. T. (1958): Cybernetica, p. 159–161.

14. Politieke maatregelen die gericht zijn op beperking van de handelsbetrekkingen met landen onder communistisch regiem vormen een hinderpaal op de weg naar vreedzame coëxistentie.

15. Het verdient aanbeveling dat de hoogleraren tijdens de uitslagen van doctoraal examens in toga gekleed zijn.

G. B. Engelen — 21 oktober 1963

# ERRATA AND ADDENDA to GRAVITY TECTONICS IN THE NW DOLOMITES (N ITALY)
by G.B. ENGELEN - 1963

p.2, column 1, line 5 should read: fig. 29 and 30 and sheet II
p.9, column 1, line 31 should read: gravity field of the earth.
p.9. column 2, line 17 should read: In both cases the mean product of mass and the square of the velocity
p.9, column 2, line 19-26 should be omitted
p.9, column 2, line 19-17 from bottom should read: global energy cluster in concentric zones of temperature equilibrium and an outward decrease of their level.
p.9, column 2, line 11 from bottom, should be omitted: of equipotential energy
p.10, column 1, line 1, should be omitted: ... energy....
p.10, column 1, line 11 should read: accompanied by non-uniform outward
p.10, column 1, line 18-19: should be omitted: ...within the equipotential surface
p.10, column 2, lines 18-19 from bottom should read: b) The foundering type: The surfaces of equal density show upward bulges or envelope
p.10, column 2, line 32 from bottom should read: a) The buoyant type: the surfaces of
p.11, fig.3, A: energy field should read: force field
p.12, column 2, line 8 shoud read: potential energy between two columns
p.13, column 2, line 10 from bottom, should be omitted:--the lowest energetic level and---
p.17, fig.10d) should read: scheme of the foundering circuits in the NW Dolomites after Engelen
p.17. fig.10 e) should read: scheme of a foundering circuit after Ramberg (1963 fig.46) 11
p.16, column 2, line II from bottom should read: such a hydraulic press system (fig.10 d).Experi-
p.16, column 2, line 9 from bottom should read: mena at a laboratory scale (see fig. 10,e)
p.18, column 1, line 13-14 should read: plate deduced the distribution of the vertical
p.18, column 2, line 20 should read: ences in potential energy of columns and the tend-
p.22, column 1, line 20 from bottom should read: since 1953 in the Eastern Alps by students of
p.43, column 2, line 3 should read: strata caused a NE-SW striking vertical normal
p. 45: fig.25, legend: direction of overthrust should read: direction of up-thrust.
p.47, column 2, last paragraph: the age of the secondary tectonics is probably older (oligo-miocene), compare the appendix.
p.51, column 1, line 7 should read: NE-SW striking, oblique fault coinciding with the
p.53, column 1, line 11 should read: austride nappes. Although during that phase
p.58, fig.51 should read fig. 31
p.63, column 1, line 12: carnian should read ladino-carnian
p.73, fig.44A and fig.44B according to Leonardi, fig.44C according to Engelen
p.84, column 2, line 2 from bottom: 3250 m should read 2250 m
p.87, column 1, line 20: Agterberg (1963) should read Agterberg (1964)
p.87, column I, line 3 should read, Alpen, II
p.89. To the literature references should be added:

BEMMELEN, R.W. van (1949): The geology of Indonesia, State Printing Office, The Hague
WHITROW, G.J. (1961): Structuur en evolutie van het heelal, Spectrum, Utrecht

Legend of sheet I, column 1, line 2, should read: pleistocene slope deposits.

# GRAVITY TECTONICS IN THE NW DOLOMITES
# (N. ITALY)

# GRAVITY TECTONICS IN THE NORTHWESTERN DOLOMITES (N. ITALY)

## PROEFSCHRIFT

ter verkrijging van de graad van doctor in de wiskunde en natuurwetenschappen aan de Rijksuniversiteit te Utrecht op gezag van de rector magnificus dr. H. Freudenthal, hoogleraar in de faculteit der wiskunde en natuurwetenschappen, volgens besluit van de senaat der universiteit tegen de bedenkingen van de faculteit der wiskunde en natuurwetenschappen te verdedigen op maandag 21 oktober 1963, des namiddags te vier uur precies

door

**GERRIT BERDINUS ENGELEN**

geboren te Arnhem

1963

DRUKKERIJ DE WERELD — EINDHOVEN

PROMOTOR: PROF. DR IR R. W. VAN BEMMELEN

AAN MIJN OUDERS

Bij de afsluiting van mijn academische studie wil ik allen danken die mij met hun belangstelling, hulp en medewerking in de afgelopen periode tot steun zijn geweest.
Hooggeleerde van Bemmelen, voor de geboden gelegenheid om bij U te promoveren ben ik zeer dankbaar. Uw stimulerende medewerking op allerlei gebied en de opbouwende critiek bij de tot standkoming van dit proefschrift heeft het werk voor mij in de afgelopen jaren tot een vreugde gemaakt. De warme, menselijke belangstelling van U en Uw vrouw ondervonden stel ik op hoge prijs.
Hooggeleerde Hol, Uw bezielde wijze van college geven en Uw belangstelling voor Uw studenten waren mij de eerste jaren van de studie tot grote steun.
Hooggeleerde Zonneveld, voor Uw onderricht in de fysische geografie, de prettige tijd waarin ik als assistent bij U werkte, de faciliteiten die U mij verleende voor het tekenwerk van dit proefschrift, en voor Uw belangstelling in het onderzoek dank ik U zeer.
Hooggeleerde Wiggers, voor alle medewerking om het proefschrift tijdig gereed te doen komen — ondervonden in de periode als Uw assistent — ben ik grote dank verschuldigd. De interesse die U steeds in mijn werk toonde waardeer ik zeer.
Hooggeleerde Rutten, U leerde mij de waarde van bedachtzaamheid en critische zin duidelijker zien op college en tijdens excursies.
Hooggeleerde Doeglas, de beminnelijke wijze waarop U tijdens college, veldwerk en practicum de sedimentologie doceerde maakte het vak voor mij levend.
Hooggeleerde Bleeker, Uw glasheldere colleges in de synoptische meteorologie en klimatologie herinner ik mij met vreugde.
Hooggeleerde Fischer, het tentamen in de volkenkunde blijf ik mij vanwege de stof en de wijze waarop U mij daarin tentamineerde met genoegen herinneren.
Hooggeleerde de Vooys, Uw onderwijs in de sociale geografie leerde mij te letten op de ruimtelijke spreiding der verschijnselen.
Hooggeleerde Berlage, Uw colleges in de meteorologie, oceanografie en klimatologie sloegen een brug tussen middelbare school en universiteit.
Hooggeleerde Edelman, Uw colleges in de regionale bodemkunde leerden mij hoe belangrijk een goed inzicht in het fysisch milieu voor het begrijpen van de menselijke samenleving is.
Hooggeleerde Nieuwenkamp, Uw colleges in de mineralogie waren voor mij een voorbeeld van academische wijsheid.
Hooggeleerde Von Koenigswald, Uw onderricht in de paleontologie en stratigrafie verschafte mij een goede basis voor verdere studie.
Hooggeleerde Vening Meinesz, U dank ik voor het onderwijs in kartografie en geodesie.
Zeergeleerde Agterberg, het werk dat ik voor Uw promotie-onderzoek deed vormde de aanleiding tot dit proefschrift. Uw vriendschap en de uitwisseling van ideeën over het onderzochte gebied waardeer ik zeer.
Weledelgeleerde Beyerinck, mijn hartelijke dank voor de stimulerende adviezen en het prettig contact met U tijdens mijn studie.
Zeergeleerde Bouma, aan Uw onderricht in de sedimentologische onderzoeksmethoden heb ik goede herinneringen.
Weledelgestrenge Frijlinck, Uw grote liefde voor het vak en grote ijver waren mij ten voorbeeld.
Zeergeleerde van Haeringen, U dank ik voor Uw tekstbesnoeiende adviezen betreffende het eerste hoofdstuk.
Zeergeleerde Koeman, de tijd die ik als assistent van U mocht werken toonde mij de waarde van systematiek en accuratesse.
Zeergeleerde Wensink, de prettige samenwerking en gedachtenwisselingen met U zullen hopelijk in de toekomst ook voortgezet kunnen worden.
Geachte van Dijk, vele malen deed ik een beroep op Uw medewerking. Steeds was U mij dan, indien mogelijk, op prettige wijze terwille, waarvoor ik U hartelijk dank.
Geachte van der Kruk, voor Uw correctie van het Engels van dit proefschrift en voor de vele plezierige gesprekken daaromheen dank ik U.
Geachte Groenewold, van Waegeningh, Vreeken en Vink, veel dank voor Uw medewerking bij het verzamelen van veldgegevens.
Geachte Heine, Wieland, Dekker en van Doorn, Uw adviezen en zorgvuldig tekenwerk maakten mede het verschijnen van dit proefschrift mogelijk. Voor de goede samenwerking mijn erkentelijkheid.
Weledelgestrenge van Lanschot, de zakelijke en prettige wijze waarop U en Uw medewerkers van het Bureau Studentenbelangen mij bij moeilijkheden steeds doeltreffend adviseerden en behulpzaam waren stel ik op hoge prijs.
De Staat der Nederlanden ben ik erkentelijk voor tijdens de studie verleende subsidies.
Ringrazio vivamente al Professore Piero Leonardi del' Istituto di Geologia dell' Università di Ferrara per le dicussioni delle probleme nel terreno, per la donazione di molte delle sue pubblicazioni e per l'interesse nelle mie investigazioni.

CONTENTS

## LIST OF ILLUSTRATIONS

## SUMMARY

The NW Dolomites (see fig. 1 and 2) have an area of approximately 1500 sq. km and are situated on the southern flank of the east alpine mountain range. The region consists mainly of permo-triassic and some younger mesozoic strata with a maximal thickness of about 3000 m. This sedimentary series was deposited unconformably on the basement of quartz phyllites, which had been metamorphosed during the hercynian orogenesis.

This thesis deals especially with the tectonic evolution of the area. The greater part of the tectonic structures of the permo-triassic strata have previously been explained by most authors, excepting Diener, Accordi and Signorini, as a result of regional, tangential compression related to the alpine orogenesis. But a study of the crucial points of the tectonics showed that an explanation of the structural evolution by means of more locally restricted gravity tectonics should be preferred.

The more general principles of the tectonic evolution of the eastern Alps, as expounded by Van Bemmelen (1960 a and b), are accepted as the tectonic setting for the structural evolution of the NW Dolomites in cenozoic time.

The NW Dolomites are the northwestern corner of the larger unit of the Dolomites. The latter unit of the southeastern Alps lagged behind during the rise of the east alpine geanticline in tertiary time. This Dolomites-block has been separated from the more elevated, central parts of the geanticline by the large Judicaria and Pusteria faults (with a vertical throw of at least 5 km). Between this fault system and the area of the Dolomites a zone of relative subsidence is intercalated, which has a graben-like or synclinal character (Brenta Alps, Val di Non area, Sarntal Alps, Pusteria Valley). From San Candido this zone extends SE-ward to San Stefano di Cadore, this tract (Valle di Sesto) separates the Dolomites from the Carnian Alps.

Parts of this depressed zone have been compressed subsequently by the gravitative spreading of the adjacent higher areas to the NW, N, and NE. (Dietzel, 1960; Van Hilten, 1960; Agterberg 1961). These authors have shown that this marginal belt along its NW, N, and NE side has been subjected to tectogenesis as a result of gravitational reactions to the rise of the east alpine geanticline.

The central part of the NW Dolomites, however, has been more or less shielded from this gravitational stress field radiating from the central alpine uplift, by the deformations of this marginal belt. In this central part of the NW Dolomites the tectonic deformations of the sedimentary cover are merely an indirect result of the alpine orogeny. The tertiary uplift of the area caused a strong erosion. This erosion created a considerable relief with more local stress fields due to relief energy. The complicated tectonic structures of the NW Dolomites appear to be almost entirely the result of the local relief-energy produced by differential erosion in the course of the cenozoic time (such as the removal of the soft La Valle and San Cassiano strata between the ladino-carnian reef masses).

The first chapter deals with general concepts of gravity tectonics: causes, types of movement, stress fields, threshold values of deformation, and trigger effects.

Chapter II discusses the main geological literature on the area, the stages of its geological mapping, and the development of the ideas on its tectonic interpretation.

Chapter III is a short review of the stratigraphy, the facies heteropy between reefs and volcanic and clastic sediments of the Middle Triassic, and the significance of the physical properties of the stratigraphic series for the cenozoic gravity tectonics.

Chapter IV contains an outline of the morphological development, which appeared to be of great importance for the tectonics. A general truncation by erosion in upper oligocene time has been followed by dissection of this surface by vertical erosion of 1000 m in miocene and lower pliocene time. A next period of lateral erosion in the upper Pliocene resulted in a lower erosion surface which is still preserved over wide tracts. This late pliocene surface has been dissected by the quaternary, vertical erosion through glaciers and rivers. On account of their relation to these tertiary erosion surfaces (pre- or post-) and their tectonic deformations many tectonic phenomena in the Dolomites could be dated.

Chapter V treats the tectonics of the crystalline basement along the northern, western, and southwestern border of the Dolomites, showing faulting, warping and plastic deformations. This alpine tectogenesis of the basement, which had already been subjected to the hercynian orogenesis, has been studied by Agterberg (1961, 1963 in press). Some additional remarks on these alpine deformations of the basement complex are made.

Chapter VI describes the tectonics of the sedimentary cover of the border zone of the Dolomites, which are induced by deformations of the crystalline basement of tertiary age, discussed in the preceding chapter. These induced tectonics involve décollement and tilting such as in the Val di Non (Van Hilten, 1960), imbrications in the rigid dolomitic cover of the Vallandro area along the northern border of the Dolomites, and subsidence of the more rigid and heavy middle parts of the sedimen-

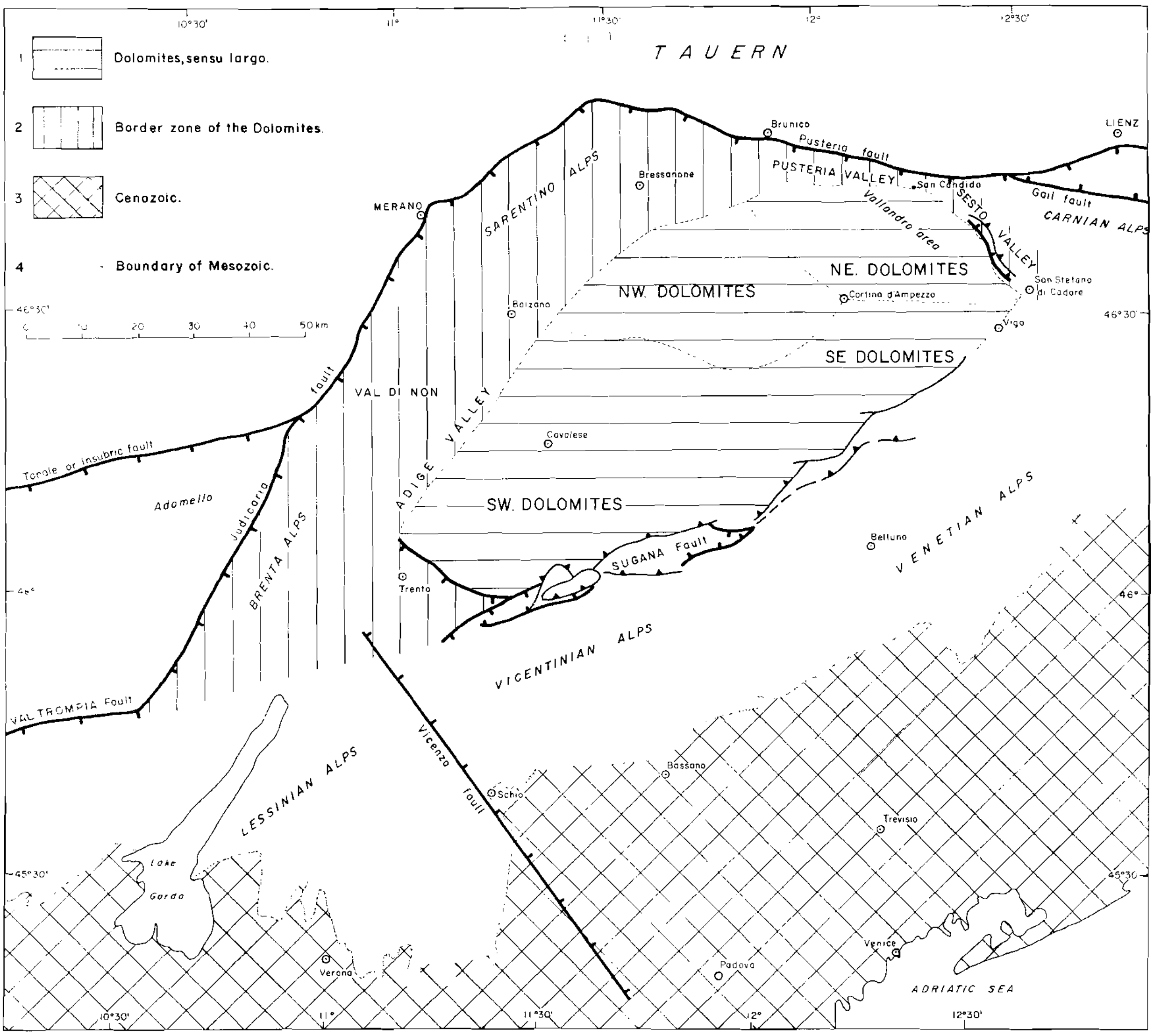



Fig. 1 Location map of the Dolomites.

tary column into their more plastic base in the Dolomites of San Vigilio and San Martino. The matter of this plastic base is strongly contorted and squeezed out and upward in domal structures (see fig. ..., and ...).

In the regional descriptions of the chapters V, VI, and VII reference is made to the concepts of gravity tectonics expounded in chapter I. In that chapter the very close resemblance is pointed out between the results of experimental studies on gravity tectonics by Ramberg (1963) and the actually observed structures of the Dolomites.

Chapter VII deals with the tectonics of the central part of the NW Dolomites, which are characterized principally by the subsidence of isolated, heavy reef masses of middle triassic age in their plastic permo-triassic base of gypsum, shales, marls, and well-bedded limestones (Bellerophon, Scythian, Anisian). During this subsidence the reefs are deformed in saucer-shaped basins, and they fall apart in blocks, squeezing the plastic matter in-between the reefs and the basement centrifugally away towards the deeply eroded valleys between the reefs, where these plastic strata formed domal structures. The Marmolada reef mass in the centre of the Dolomites, however, was domed up by a centripetal flow of the plastic matter beneath it, and it was pierced diapirically in a later stage of its evolution.

Slabs of the upper part of the sedimentary series (Norian, Jurassic, Cretaceous) slid from the tilted edges of the reefs and from the flanks of the

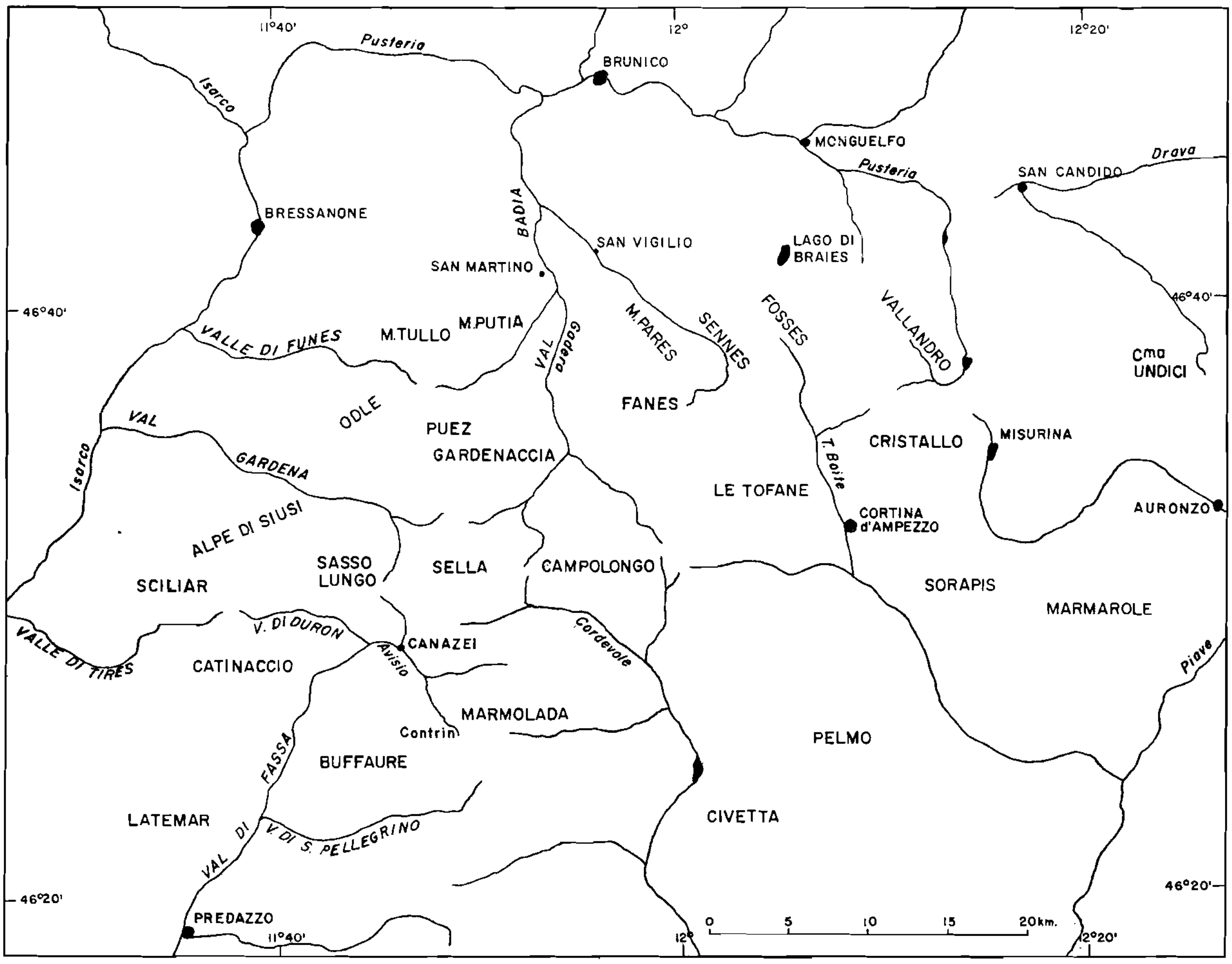



Fig. 2 Location map of the principal mountain groups of the Dolomites.

primary domes between the reefs towards the depressed centres of the reef masses. These gliding tectonics resulted in very intense deformations (summit folding and summit thrusting) in the younger strata on the top of the more competent, broken, and slightly tilted reef masses. The tectonic deformations of the reefs, their base and surroundings, and their summital structures all belong to one coherent, local energy system. The reef masses, carved out as huge blocks loaded with potential energy by the selective cenozoic erosion, acted as the plungers of a hydraulic press.

At the beginning of the Tertiary the drainage pattern was carved more or less at random in the upper part of the stratigraphic sequence which has a rather uniform facies distribution (Cretaceous, Jurassic and upper Triassic). The drainage was concentrated, however, during oligo-miocene time as the river valleys were incised into the easily erosible strata between the reefs (La Valle and Cassiano facies of the Ladinian). This selective erosion induced the subsidence of the reef masses into their plastic base, squeezing it out towards the adjacent valley floors, which were bulged up because of this accrue of matter. The drainage pattern glided from these primary bulges, so that the latter became surrounded by annular drainage systems. Consequently, in the landscape the preceding erosion chiseled out these primary domes thus producing bulges loaded with their own potential energy.

These primary domes then began to collapse under their own weight and by the undercutting activity of the incising rivers around.

The plastic contents of the domes were pushed out sidewards, towards the carves of the valleys, thus forming second order diapirs which pierced the valley walls in a lateral direction. These young cenozoic lateral diapirs have thus far been described in the literature as the effects of supposedly triassic volcano-tectonic dislocations. These lateral diapirs occurred successively in subsequent lower levels, related to the stages of incision of the valleys in young cenozoic time. The floors of the deepest valleys are occasionally pushed vertically upward (Cordevole) by the load pressure from the surrounding masses.

Summing up it can be said that the subsidence of the ladino-carnian reef masses and the deformations of the plastic matter beneath and around them (Bellerophon, Scythian, Anisian) started in the Oligocene and still continue in the present time.

## SAMENVATTING


De NW Dolomieten (zie overzichtskaartjes fig. 1 en 2) hebben een oppervlakte van ongeveer 1500 $km^2$ en liggen op de zuidflank van de oost-alpiene keten. Het gebied is hoofdzakelijk opgebouwd uit permo-triadische en nog wat jongere mesozoische sedimenten met een maximale dikte van ongeveer 3000 m. Deze sedimentaire serie werd discordant afgezet op de kristallijne ondergrond van kwartsphyllieten, die gemetamorfoseerd zijn tijdens de hercynische gebergtevorming.

Dit proefschrift behandelt voornamelijk de tectonische ontwikkeling van het gebied. Het grootste deel van de tectonische structuren in de permotriadische lagen is vroeger door de meeste onderzoekers, afgezien van Diener, Accordi en Signorini, verklaard als een gevolg van regionale, tangentiele druk verbonden met de alpiene gebergtevorming. Een onderzoek van de beslissende punten van de tectoniek toonde aan dat de voorkeur gegeven dient te worden aan een verklaring van de structurele ontwikkeling door middel van zwaartekrachtstectoniek van slechts locale omvang.

De meer algemene beschouwingen over de tectonische ontwikkeling van de Oostalpen, zoals die uiteengezet zijn door van Bemmelen (1960, a en b), worden aanvaard als het grotere tectonische kader voor de structurele ontwikkeling van de NW Dolomieten in het Kaenozoicum.

De NW Dolomieten vormen de noordwestelijke hoek van de grotere eenheid der Dolomieten. Deze eenheid van de zuidoostelijke Alpen bleef achter tijdens het omhoog rijzen van de oostalpiene geanticlinaal in het Tertiair. Dit Dolomieten blok is gescheiden van de meer opgeheven, centrale delen van de geanticlinaal door de grote Judicaria en Pusteria breuken (met een spronghoogte van minstens 5 km). Tussen dit breuksysteem en het gebied van de Dolomieten is een zone van relatieve daling, die van slenk-achtige of synclinale aard is (Brenta Alpen, Val-di-Non gebied, Sarntaler Alpen, Pusteria dal). Deze zone strekt zich van San Candido uit naar het zuidoosten naar San Stefano di Cadore, dit deel (Valle di Sesto) scheidt de Dolomieten van de Karnische Alpen. Delen van deze gedaalde zone zijn later samengedrukt door de gravitatieve spreiding van de nabijgelegen hogere gebieden in het noordwesten, het noorden en het noordoosten (Dietzel, 1960; van Hilten, 1960; Agterberg, 1961). Deze auteurs hebben aangetoond dat deze randzone langs de NW, N en NO zijde tectogenese heeft ondergaan ten gevolge van gravitatieve reacties op het omhoog komen van de oostalpiene geanticlinaal.

Door de vervormingen in deze randzone is het centrale deel van de NW Dolomieten echter min of meer beschut gebleven tegen dit gravitatieve spanningsveld dat uitstraalde vanuit de centrale, alpiene opheffing. In het centrale deel van de NW Dolomieten zijn de tectonische vervormingen van de sedimentaire bedekking louter een indirect gevolg van de alpiene gebergtevorming.

De opheffing van het gebied in het Tertiair veroorzaakte een sterke erosie. Deze erosie schiep een aanzienlijk relief met daarin meer locale spanningsvelden als gevolg van reliefenergie. De ingewikkelde tectonische structuren van de NW Dolomieten blijken vrijwel geheel het gevolg te zijn van de locale reliefenergie, veroorzaakt door ongelijkmatige erosie in de loop van het Kaenozoicum (het opruimen van de zachte La Valle en San Cassiano lagen tussen de ladino-carnische riffen).

Het eerste hoofdstuk behandelt algemene beginselen van zwaartekrachtstectoniek: oorzaken, bewegingstypen, spanningsvelden, drempelwaarden voor vervorming en aanleidingen tot deformatie.

Hoofdstuk II bespreekt de belangrijkste geologische literatuur over het gebied, de stadia van de geologische kartering en de ontwikkeling in de opvattingen over de tectonische verklaring.

Hoofdstuk III is een kort overzicht van de stratigrafie, de facies heteropie tussen riffen en vulkanische en klastische afzettingen van de midden Trias, en de betekenis van de fysische eigenschappen van de stratigrafische serie voor de kaenozoische zwaartekrachtstectoniek.

Hoofdstuk IV bevat een schets van de morfologische ontwikkeling, welke van groot belang bleek te zijn voor de tectoniek. Een algehele vervlakking door erosie in het boven Oligoceen werd gevolgd door de versnijding van dit oppervlak door verticale erosie van plm. 1000 m tijdens het Mioceen en het onder Plioceen. Een volgende periode van laterale erosie tijdens het boven Plioceen had een lager gelegen erosievlak tot gevolg, dat nog over grote uitgestrektheden bewaard is gebleven. Dit laatpliocene oppervlak is versneden door de kwartaire verticale erosie door gletschers en rivieren. Vele tectonische verschijnselen in de Dolomieten konden gedateerd worden door hun relatie tot deze erosievlakken (voor of na) en de tectonische vervormingen van de laatstgenoemde vlakken.

Hoofdstuk V behandelt de tectoniek van de kristallijne ondergrond langs de noordelijke, westelijke en zuidwestelijke rand van de Dolomieten, waarin breukvorming, verbuigingen en plastische vervormingen voorkomen. Deze alpiene tectogenese van de ondergrond, die al getroffen was door de hercynische gebergtevorming, is bestudeerd door Agterberg (1961, 1963 in druk). Enkele aanvullende opmerkingen over deze alpiene deformaties van de kristallijne ondergrond worden gemaakt.

Hoofdstuk VI beschrijft de tectoniek van de sedimentaire bedekking van de randzone van de Dolomieten, die teweeg gebracht is door vervormingen van tertiaire ouderdom van de kristallijne ondergrond, besproken in het voorgaande hoofdstuk. Deze afgeleide tectoniek omvat: afglijding en scheef stelling zoals in het Val di Non (van Hilten, 1960); dakpansgewijze verschubbingen in de stijve dolomitische bedekking van het Vallandro gebied (NO Dolomieten); en inzakken van de stijvere en zwaardere, middelste delen van de sedimentaire kolom in de meer plastische basis in de Dolomieten van San Vigilio en San Martino. Het materiaal van deze plastische onderlaag is sterk vervormd en opwaarts weggeknepen naar koepelvormige structuren.

In de regionale beschrijvingen van de hoofdstukken V, VI, en VII wordt verwezen naar de begrippen van zwaartekrachtstectoniek die in hoofdstuk I uiteengezet zijn, en waarin gewezen wordt op de zeer grote overeenstemming tussen de resultaten van experimentele studies van zwaartekrachtstectoniek door Ramberg (1963) met de feitelijk waargenomen structuren van de Dolomieten.

Hoofdstuk VII betreft de tectoniek van het centrale deel van de NW Dolomieten, die hoofdzakelijk gekenmerkt wordt door het inzakken van geïsoleerde, zware rifmassa's van middentriadische ouderdom in hun plastische, permo-triadische onderlaag van gips, schalies, mergels en goedgelaagde kalken (Bellerophon, Skyth, Anis). Tijdens deze inzakking worden de riffen vervormd tot komvormige bekkens en vallen ze uiteen in schollen, tegelijkertijd het plastische materiaal tussen de riffen en de kristallijne ondergrond centrifugaal weggepersend naar de diep ingesneden dalen tussen de riffen, waar deze plastische lagen koepelvormige structuren vormen.

Het Marmolada rif in het centrum van de Dolomieten werd echter opgewelfd door een centripetale vloei van het plastische materiaal eronder en is in een later stadium van zijn tectonische ontwikkeling diapier doorbroken.

Schollen van het bovenste deel van de sedimentaire serie (Nor, Jura, Krijt) gleden van de scheefgestelde randen van de riffen en van de flanken van de primaire koepels tussen de riffen naar de gedaalde centrale delen van de rifmassa's toe. Deze glij-tectoniek had zeer intensieve vervormingen (top-plooiingen en top-overschuivingen) in de jongere lagen bovenop de meer competente, gebroken en enigszins scheef gestelde riffen tot gevolg. De tectonische vervormingen van de riffen, van hun ondergrond en omgeving, en de structuren op de toppen behoren allen tot een samenhangend, locaal energiesysteem. De rifmassa's, als geweldige blokken uitgeprepareerd en geladen met potentiele energie door de selectieve kaenozoische erosie, werken als de zware zuigers van een hydraulische pers.

In het begin van het Tertiair was het afwateringspatroon min of meer willekeurig ingesneden in het bovenste deel van de stratigrafische opeenvolging, die een tamelijk eenvormige faciesverdeling heeft (Krijt, Jura en boven Trias). De afwatering werd tijdens het Oligo-Mioceen echter geconcentreerd daar de rivieren zich insneden in de gemakkelijk erodeerbare lagen tussen de riffen (La Valle en San Cassiano facies van het Ladinien). Deze selectieve erosie gaf aanleiding tot het inzakken van de rifmassa's in hun plastische onderlaag, deze daarbij uitknijpend naar de nabijgelegen depressies, die opgewelfd werden door de toevoer van materiaal. Het afwateringspatroon gleed van de opgewelfde primaire koepels af, zodat ze omringd werden door min of meer ringvormige afwateringssystemen. Dientengevolge prepareerde de voortgaande erosie deze primaire koepels uit in het landschap, zodoende opwelvingen veroorzakend die beladen waren met hun eigen potentiele energie. Deze primaire koepels begonnen toen in te zakken onder hun eigen gewicht en door de ondergravende werking van de zich insnijdende rivieren rondom. De plastische inhoud van de koepels werd zijdelings weggedrukt naar de insnijdingen van de dalen en op deze wijze werden diapieren van de tweede orde gevormd, die de dalwanden in zijdelingse richting doorbreken. Deze jong kaenozoische, laterale diapieren zijn tot dusver in de literatuur beschreven als de effecten van veronderstelde, triadische vulcano-tectoniek. De zijdelingse diapieren traden achtereenvolgens op lagere niveaux op, die gebonden zijn aan de stadia van insnijding van de dalen in jong kaenozoische tijd. De dalbodems van de diepste dalen worden soms verticaal omhoog gedrukt (Cordevole) door de belastingdruk ten gevolge van de omgevende massa's.

Samenvattend kan men zeggen dat de inzakking van de ladino-carnische rifmassa's en de deformaties van het plastische materiaal eronder en rondom (Bellerophon, Skyth, Anis) begonnen in het Oligoceen en nog voortduren in het heden.

## RIASSUNTO


Le Dolomiti nordoccidentali hanno una superficie di alquanto 1500 km$^2$ e si trovano sul fianco meridionale della catena alpina sud orientale. La regione è costituita principalmente di strati permo-triassici e qualche più recenti strati mesozoici, con un spessore massimo di 3000 m. Questa serie sedimentaria fu depositata discordantemente sul basamento di filladi quarzifere, le quale furono metamorfosate durante l'orogenesi ercinica.

Questa tési tratta especialmente l'evoluzione tettonica dell'area. La più gran parte delle strutture tettoniche nei strati permo-triassici furono descritte dapprima dalla maggioranza dei autori, esclusi il Diener, l' Accordi e lo Signorini, come risultati di compressione regionale e tangenziale in relazione coll' orogenesi alpina. Però, lo studio dei punti di quintessenza ha dimostrato che sia preferibile un' esplicazione dell' evoluzione tettonica a mezzo della tettonica per gravità di estensione piu locale.

Le linee generali dell' evoluzione tettonica delle Alpi orientali come esposte dal Van Bemmelen (1960 a e b) sono prese come il quadro più largo per l'evoluzione strutturale delle Dolomiti nordoccidentali in tempo caenozoico.

Le Dolomiti nordoccidentali formano l'angolo nordoccidentale dell' unità più larga delle Dolomiti entiere. La quale rimaneva in giù durante l'ascensione della geanticlinale alpina orientale nel Tertiario. Questo blocco delle Dolomiti fu separato delle parti centrali della geanticlinale emergente, dalle grandi faglie di Judicaria e Pusteria (con un' abbassamento di almeno 5 km). Fra questa sistema di faglie e la regione dolomitica si trova una zona di abbassamento relativo con carattere di synclinale o di graben (Alpi di Brenta, Val di Non, Alpi Sarentine, Val Pusteria, Valle di Sesto). La zona si estende verso sudest da San Candido fino a San Stefano di Cadore e separa le Dolomiti dalle Alpi Carniche. Poi, qualche parti di questa zona abbassata furono compresse per la distensione gravitativa dei terreni vicini verso nordovest, nord e nordest (Dietzel, 1960; Van Hilten, 1960; Agterberg, 1961). Questri autori hanno dimostrato che la zona marginale ha tettogenesi ai lati nordoccidentali, settentrionali e nordorientali, risultanda dalle reazioni gravitative per l'ascensione della geanticlinale alpina orientale.

Le parti centrali delle Dolomiti nordoccidentali, nondimeno, sono state preservate dall' influenza di pressione gravitativa, raggiante della geanticlinale emergente a causa dalle deformazioni nella zona marginale. In questa parte centrale delle Dolomiti nordoccidentali le deformazioni della copertura sedimentaria sono solamente un resultato indiretto dell' orogenesi alpina. Il sollevamento della regione nel Tertiario causava una forte erosione.

L'erosione produceva un relievo importante con zone di pressione di estensione limitata a causa dell' energia di relievo.

Appare che le complicatissime strutture tettoniche delle Dolomiti nordoccidentali centrali sono quasi tutte il resultato della energia locale di relievo, prodotto dall' erosione selettiva durante il periodo caenozoico (l' evacuazione dei strati teneri di La Valle e di San Cassiano fra le scogliere ladino-carniche).

Il primo capitolo tratta i concetti generali della tettonica per gravità; le cause, i tipi di movimento, i valori di soglia per la deformazione etc.

Nel secondo capitolo si discute le pubblicazioni geologiche importanti sulla regione, le scale di rilevamento geologico e l'evoluzione delle idee sull' interpretazione tettonica.

Il terzo capitolo contiene un compendio della stratigrafia, della facies eteropica di scogliere e depositi volcanici e clastici del Trias medio, e l'importanza delle proprietà fisiche della serie stratigrafica per la tettonica per gravità di età caenozoica.

Il quarto capitolo comprende un schizzo della storia morfologica che apparisce di gran valore per la tettonica. Un spianamento generale dall' erosione nell' Oligocene superiore fu seguito dalla taglia di questa superficie per l'erosione verticale di alquanto 1000 m nel Miocene en nel Pliocene inferiore. Un seguente periodo di erosione laterale nel Pliocene superiore risultava in una superficie di erosione più bassa che è stata preservata ancora in grandi tratti. Questa superficie del Pliocene superiore è tagliata dall' erosione verticale dei ghiacciai e dei fiumi. Era possibile di datare molti fenomeni tettonici nelle Dolomiti a causa delle relazioni con queste superficie di erosione (prima di o dopo di) e le deformazioni delle ulteriori.

Il quinto capitolo tratta la tettonica del basamento cristallino lungo i margini settentrionali, occidentali e sudoccidentali delle Dolomiti, nei quali occorrono faglie, ondazioni e deformazioni plastiche. La sudetta tectogenesi alpina del basamento (già deformato dall' orogenesi ercinica) fu studiato da Agterberg (1961, 1963 in corso di stampa) ed altri. Qualche osservazioni addizionali su queste deformazioni alpine del basamento sono procurate.

Il sesto capitolo descrive la tettonica della copertura sedimentaria della zona marginale delle Dolomiti, causata dalle deformazioni del basamento cristallino nel Tertiario (vedasi il capitolo precedente). Questa tettonica derivata comprende scivolamenti come nel Val di Non (van Hilten,

1960); scaglie embricate nella coltre rigida dolomitica della regione di Vallandro (Dolomiti nordorientali); e l'abbassamento delle parte medie (piu rigide e pesanti) della colonna sedimentaria nella sua base di materiali più plastici delle Dolomiti di San Vigilio e San Martino in Badia. I strati di questa zona plastica sottostante furono contorsi e spremuti all' insù verso strutture con forme di cupola.

Nella descrizione dei capitoli V, VI e VII si referisce ai concetti di tettonica per gravità, esposti nel capitolo primo e si indica la conformità molto precisa fra i resultati di studi esperimentali di tettonica per gravità (Ramberg, 1963) e le strutture osservate nel terreno Dolomitico.

Il settimo capitolo discute la tettonica della parte centrale delle Dolomiti nordoccidentali, che e caratterizata principalmente dal abbassamento gravitativo delle masse isolate di scogliera di età medio-triassica nella zona plastica sottostante di gesso, marne e calcari fittamente stratificati. Durante l'abbassamento le scogliere sono deformate in forma di scodella, spremendo nel stesso tempo i materiali plastici fra le scogliere ed il basamento verso le valli. Le valli sono profondamente tagliate tra le scogliere, ove le formazioni plastiche formano strutture a forma di cupola.

La scogliera della Marmolada, nel centro, delle Dolomiti, nondimeno, fu sollevata dal movimento centripetale dei materiali plastici sottostanti, e fu perforata dal diapirismo in uno stadio seguente dalla sua evoluzione tettonica.

Parti della parte superiore della serie sedimentaria (Norico, Giurese, Cretaceo) scivolavano dei margini rovesciati e dei fianchi delle cupole primarie tra le scogliere verso le parti centrali abbassate delle scogliere. Questa tettonica di scivolamento causava deformazioni intensi (dislocazioni delle cime) nei strati più recenti sulle scogliere rigide, che erano tagliate da faglie e rovesciate alquanto. Le deformazioni tettoniche delle scogliere, dei strati in giù e dei terreni circondanti e le dislocazioni delle cime fanno parte di un' unica sistema di energia connessa e locale. Le masse delle scogliere (isolate come blocci giganteschi e forniti di energia potenziale dall' erosione selettiva caenozoica) agiscono come i pistoni pesanti di un torchio idraulico.

Nel comincio del Tertiario la rete idrografica fu tagliata più o meno arbitrariamente nella parte superiore della serie sedimentaria chi ha una facies abbastanza uniforme (Cretaceo, Giurese e Triassico superiore). Il scolo fu concentrato però, nel' Oligocene-Miocene perchè i fiumi intaccavano i strati di facile erosibilità tra le scogliere (strati di La Valle e di San Cassiano della facies eteropica del Ladinico). Quest' erosione selettiva causava l'abbassamento delle masse di scogliera nel loro fondamento plastico e lo spremendolo verso i fondovalli vicini chi erano sollevati da questa affluenza di materie. La rete idrografica scivolava in giù da queste cupole primarie così che le sudette scogliere erano circondate da sisteme idrografiche più o meno in forma di cerchio. In conseguenza l'erosione continuante sbucciava quelle cupole primarie nel paesaggio, causando così sollevamenti topografici colla loro propria energia di relievo. Le cupole primarie cominciavano a crollare sotto l'influenza del loro proprio peso e dall' azione scavante dei fiumi che intaccavano intorno. Il contenuto plastico delle cupole era spremuto lateralmente verso le intaccature delle valli e in questo modo se formavano diapiri di secondo ordine che perforavano lateralmente i fianchi delle valli. Queste strutture diapiriche laterali di età caenozoica superiore sono stati descritti fino adesso nella letteratura come gli supposti effetti di volcano-tettonica non-orogenica del Triassico. I diapiri laterali si formavano successivamente in livelli più bassi, connessi coll' intaccatura delle valli nel Caenozoico superiore.

I fondovalli delle valli più basse sono sollevati talora (Cordevole) dalla pressione gravitativa effettuata dalle masse circondante.

Riassumendo può essere detto che l'abbassamento delle masse di scogliera ladino-carniche e le deformazioni dei materiali in giù ed intorno (Bellerophon, Werfeniano, Anisico) cominciava nell' Oligocene e continua ancora nel tempo d'oggi.

bij een afgesloten proces neemt de entropie toe of blijft gelijk.
gevolg: equipartitie van energie is gevolg of ...

# CHAPTER I

# GRAVITY TECTONICS, GENERAL CONCEPTS

## I, 1. INTRODUCTION.

The tectonic deformations discussed in this thesis are considered as the results of primary vertical movements (primary tectogenesis) and the ensuing gravitational reactions to it (secondary tectogenesis), according to the concepts of Haarmann (1930) and Van Bemmelen (1931, 1954, 1960).

The terminology used in this thesis was chosen preferably in accordance with the Geological Nomenclature of the Royal Geological and Mining Society of the Netherlands, edited by Schieferdecker (1959). The symbols for structural phenomena of maps and sections were mainly derived from the Standard Legend of the Royal Dutch/Shell Group (1958).

New symbols were used for rotational block movements and diapiric fault contacts. Rotational block movements are indicated in this thesis by a closed cross bar which is parallel to the axis of rotation of the block, combined with an open arrow pointing in the direction of the downward rotated side of the block. Diapiric contacts are indicated by means of a fault line with closed triangles at the side of the diapiric mass, and barbs at the other side of the line pointing towards the enveloping country rock. If desired, small arrows pointing in the direction of dip of the fault plane can be added.

In the next pages an attempt is made to set up a scheme of tectonic deformations in terms of the potential energy of masses of rock in relation to the ~~gravitational energy~~ gravity field of the earth.

g = force?

## I, 2. SOME GENERAL REMARKS ON THE ENERGY LAWS.

The first law of thermodynamics or the law of konservation of energy is also known as the energy principle. It states that:

(a) The total amount of energy does not change if a ~~system~~ closed is not subjected to external influences.

(b) The total amount of energy of a ~~system~~ closed decreases with the amount of work, exerted by the system on its surroundings.

(c) The total amount of energy of a system increases with the amount of work exerted by external forces on the system.

This law has retained its universality, even during the enormous progress in science during the last decades.

The second law of thermo-dynamics states something about the direction of energetic processes. Heat cannot move spontaneously from a colder to a warmer body, or as a statistical rule: with every process in which work is exerted a part of the free energy is transformed into thermal energy.

We consider the second law of thermo-dynamics as a particular case of a still more fundamental law: the law of the tendency to a stable energy distribution. Such a stable energy distribution does not necessarily mean the absence of differentiation in the way the energy is distributed in a system. This might be demonstrated with some examples. An equal distribution of energy over the components has been found by Maxwell for a mixture of two gases and by Halm for the stars in the universe (Withrow, 1961, p. 194).

In both cases the mean product of mass and ~~velocity~~ square of is about equal for the components of the system. Another example in which this is still more evident is the pouring out of loose, dry sand. The formed heap of sand will acquire a constant maximal angle of repose (the stable energy gradient or potential curve) if sand is continuously added to the top. The surplus will be transported down slope and the cone will gradually rise and broaden, maintaining meanwhile its maximum angle of repose.

verkeerd gebruik van begrippen energie en potentiaal!

## I, 3. STABILITY OF MASS DISTRIBUTION IN A HORIZONTAL SENSE.

The subdivision of the earth in concentric layers (core, mantle, crust, hydrosphere, and atmosphere) can be considered as a first rough subdivision of the global energy cluster in concentric zones of ~~energetic~~ equilibrium and an outward decrease of their ~~energy~~ level. Within each of these ~~equipotential~~ zones a certain equilibrium has already been established, but a constant outward flow of endogenic energy still occurs. Lateral flows of energy should not be necessary if the radially outward flow of energy were perfectly equal in all directions, so that each level of ~~equipotential~~ energy would transmit in every square unit of area the same amount of energy per unit of time. If the distribution of the outward flow of energy is irregular, tangential flows of energy must occur.

The rocks of the crust would be in a stable situation—without the tendency to lateral movements—if the distribution of the mass were perfectly equal in a lateral sense and parallel to the equipotential surfaces of the earth' gravitational field. As long as this situation has not been reached lateral movements of mass will occur if the ~~energy~~ force gradients of ~~potential energy~~ are steep enough to overcome the threshold values (cohesion of the rocks) resisting to a perfect lateral spreading. The case of isostatic equilibrium must be considered consequently as an uncomplete equilibrium, in which the rocks still have the tendency to spread further in order to reach hydrostatical equilibrium (see for instance Van Bemmelen, 1954, p. 115; Engelen, 1963, p. 74).

Primary vertical movements in the crust are considered as the result of non-uniform outward flow of energy in the earth, causing deviations from a uniform mass distribution in lateral sense (primary tectogenesis). Lateral movements of mass tend to spread the local accumulation of mass (and its associated potential energy) by the processes of erosion and gravity tectonics (secondary tectogenesis) causing a diminuation of such anomalies ~~within the equipotential surface~~.

The secondary tectonics can occur at different levels in the crust and have each their specific types of movement and deformation dependent on the differing physico-chemical and mechanical circumstances at those levels. Epidermal gravity tectonics, affecting the sedimentary cover of the crust, dermal gravity tectonics for the more rigid basement complex, bathydermal gravity tectonics for the lower, more plastic and migmatized part of the crust, and subcrustal gravity flow for the substratum can be distinguished. This leads to a differential way of tectonic deformation, not only in the various levels of the crust (in german: "Stockwerke"), but also for the earth layers beneath the Mohorovicic discontinuity down to the very centre. This has led Van Bemmelen (1963) to the draft of a more general geotectonic synthesis of relativistic character, called "Stockwerk-geotectonics".

For instance, it is possible that the crustal part, which forms the base of the Dolomites has been transported as a whole due to flow movements in deeper levels, as is suggested by the paleomagnetic work of De Boer (1963). This assumed permo-mesozoic drift did not affect then the shallower epidermal and mesodermal stories, which were deformed later, during the alpine tectogenesis in tertiary time. It is this later structural history of the sedimentary cover or epiderm, which forms the major topic of this thesis.

## I, 4. VERTICAL TRANSFER OF ENERGY IN THE CRUST.

Each major storey or "Stockwerk" is a more or less coherent, independent energetic system with its own definite threshold values for storage of energy: storage of potential energy by elastic strain, storage of physico-chemical energy by rise of temperature, changes of mineral paragenesis, or even (partial) melting. As long as these threshold values are not surpassed, the deformations and transformations will be restricted to the major zones themselves. Only if the addition of energy to the zone becomes greater than its storage capacity, which means the passing of one of those threshold values, the zone will transmit energy to the next higher zone.

The upward transfer of energy from one major zone to another will be preceded by a period of internal physico-chemical transformation and/or deformation within that zone, untill its energy storage capacity is surpassed. This has been called the "incubation period".

The energy will then be spasmodically released and transmitted to the next higher zone, which process may be accompanied by disturbances along the boundary between the two zones. The radially outward flow of endogenic energy through the stories of the crust has a more or less spasmodical and periodical character like a relaxation pulsation (tectogenetic or orogenetic phases), Van Bemmelen, 1954, p. 163.

## I, 5. STABILITY OF MASS DISTRIBUTION IN A VERTICAL SENSE.

Vertical stability requires an increase of specific weight with depth. See for a stable specific weight curve fig. 3 a.

Van Bemmelen (1958, 1960) has pointed out that two types of deviation from gravitational equilibrium in a vertical sense are possible:

a) **The buoyant type:** the ~~equipotential~~ surfaces of equal density show downward bulges or envelope an isolated area with low density. Archimedian, upward forces will try to move the low density body upward untill it has reached its appropriate stable position at the place where its energy potential in relation with its specific weight fits in the stable specific weight curve.

b) **The foundering type:** The ~~equipotential~~ surfaces of equal density show downward bulges or envelope isolated areas with high density. Newtonian, gravitational forces will try to pull the high density body downward untill it has reached a stable position and fits in the stable specific weight curve. The heavy body resembles the plunger of the energetic system of a hydraulic press. The vertical movements start as soon as the deviations from the stable density layering have become important enough to create the stresses which are necessary to overcome the threshold values of the strength of the rocks.

Restoration of the gravitational equilibrium by buoyant or foundering movements causes flow circuits of masses: updoming with intrusion (vertical diapirism) of the overlying masses in the first case; and subsidence with squeezing away of the underlying matter in the second case. The rising matter has a gain in potential energy, the subsiding matter shows a decrease of it. The foundering or rising of masses is accompanied by the reverse movements of masses in its surroundings, as a volumetric compensation within the one coherent energy system. The energy system of the mass circuit looses a part

Zeker erg pleonastisch!

bedoeld is: zelfs worden deze begrip, kracht ↓
lichter .. .. , kracht ↑

begrippen energie en kracht
worden verward
Zie blz 9, onder I,1.

woord energy dat energie aan.

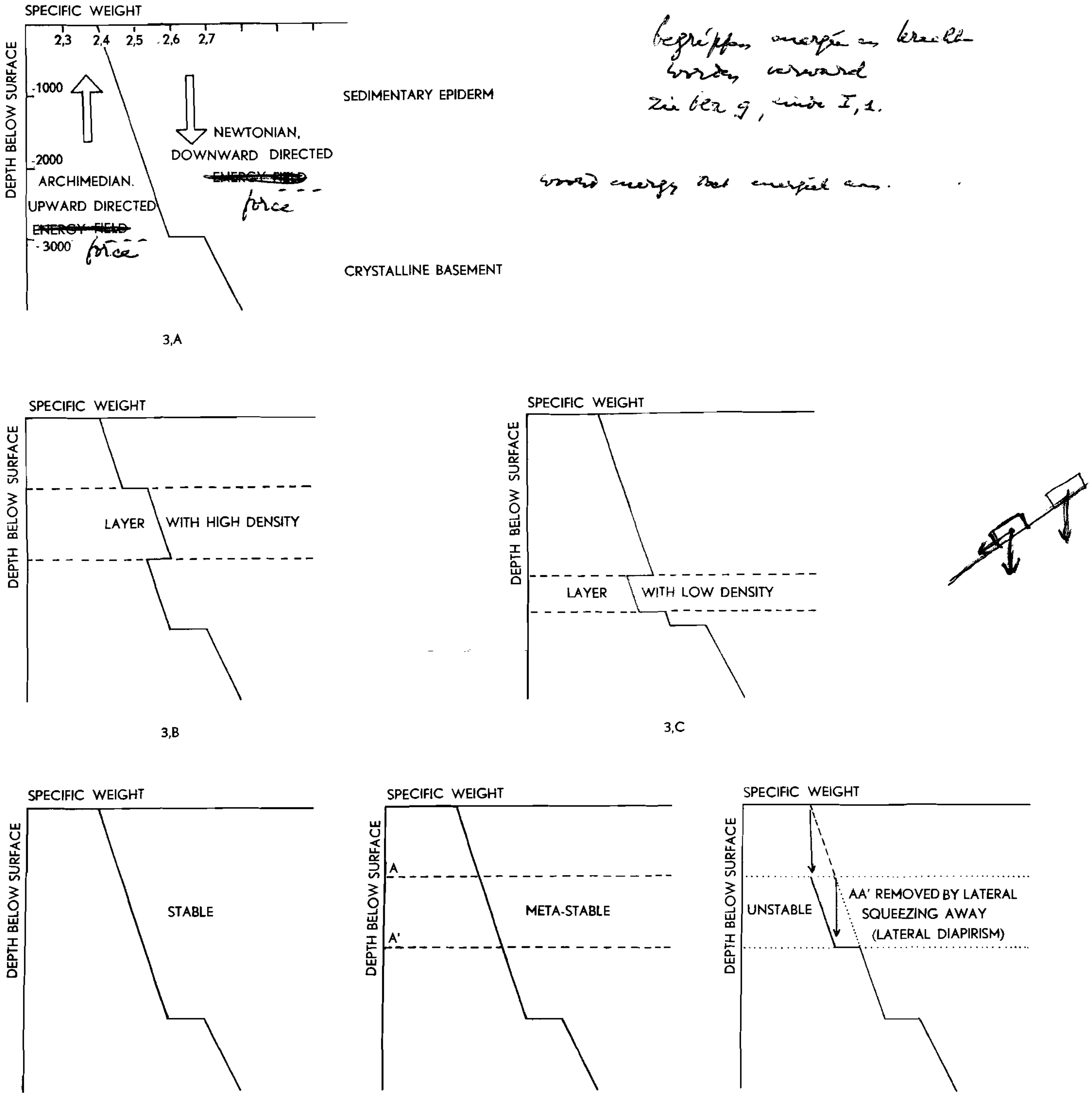



Fig. 3 Types of density stratification and stability conditions. a) stable density stratification b) condition for a foundering circuit with Newtonian downward movement c) condition for a buoyant circuit with Archimedian upward movement d) stable situation, the strength of the rocks withstands the load pressure e) meta-stable situation, the layer AA' would yield through the load pressure if a possibility of sideward escape existed f) unstable situation, the layer AA' yields through the load pressure and is squeezed laterally away, whereas the overlying strata subside.

of its total potential energy, which is used for the deformation and movement of the masses. This free energy of the system is transformed into low level thermal energy, which is finally lost by radiation into space.

Fig. 3, a, b and c demonstrate the change of specific density with depth for the stable case and for the unstable situations which give rise to foundering or buoyancy. Even if a stable density layering is found, a meta-stable situation occurs if the load pressure in a part of the vertical section exceeds the strength of the rock (fig. 3 e) and if then a possibility of sideward escape exists (fig. 3 f). Horizontal squeezing out of that part of the section is then the result. This has been suggested for instance by Raven (1959, p. II) to account for the lip of granitic basement rocks along the continental margins around the Atlantic Ocean ("continental outflow"); by Van Bemmelen for the genesis of the Pennine nappes by lateral injection (1960); and it was found also at a much smaller scale in the collapse of primary domes of sediments which caused lateral diapirs in the surrounding valley walls in the NW Dolomites.

## I, 6. INTENSITY AND REGIONALITY OF GRAVITATIONAL STRESS FIELDS, THRESHOLD VALUES.

The amount of potential energy of an elevated mass is a function of its specific density, volume, and the altitude above the lowest point of the surroundings. The elastic strain and the accompanying stress gradients, arising form local differences in amount of potential energy within the earth' gravitational field depend on:
(1) the algebraic difference in the amounts of potential energy between two points ?
(2) their mutual distance
(3) the existance of maximum values for stress accumulation (strength threshold values).
If the gradient caused by the factors 1 and 2 is not sufficient to overcome the threshold values for deformation, a stable situation without movements of masses exists. In many cases, however, such a stable situation is only apparent.

The strength of rocks has often been overestimated by application of engineering concepts which are based on stress-strain experiments of short duration. It becomes more and more obvious that the rocks behave as fluids of low viscosity instead of elastic solids when great loads are applied and when they are subjected to stress for a very long time (see among others Van Bemmelen, 1931, 1950, 1954, p. 94; Hamilton, 1962; Carey, 1962). The rock layers strive for hydrostatical equilibrium in the gravitational field; this makes that they are under elastic strain as long as this equil-

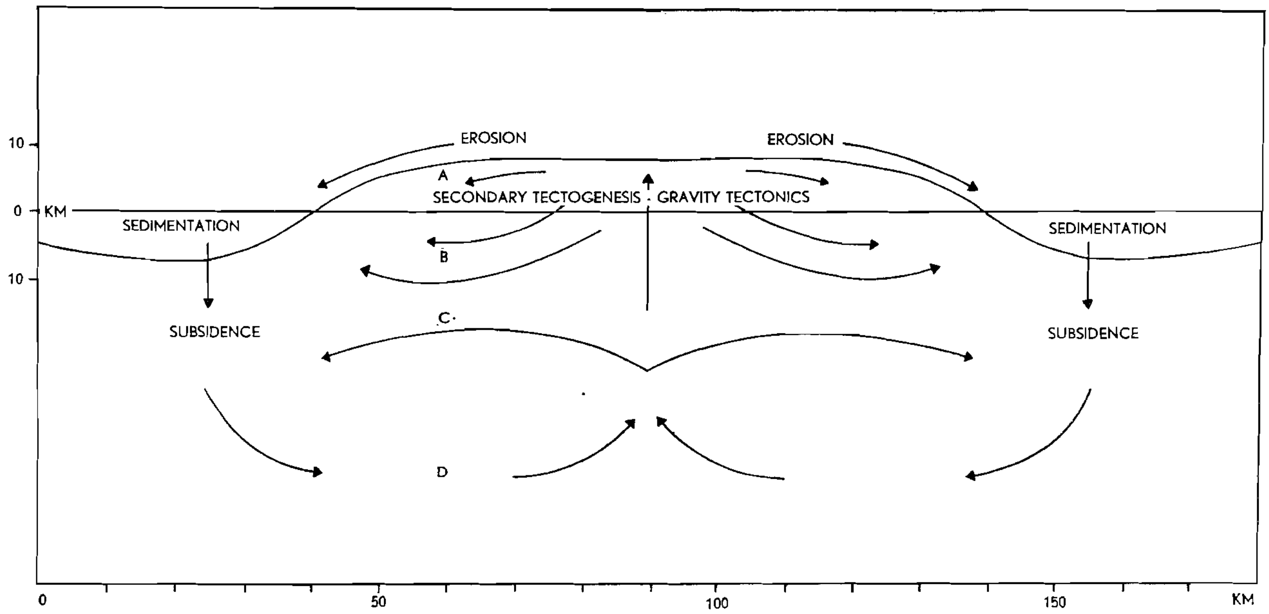



Fig. 4 The orogenetic mass circuit, after Van Bemmelen (1955, fig. 1). Uplift by endogenetic causes (primary tectogenesis) and lowering of the relief by gravitative reactions (secondary tectogenesis).
a = epidermal tectogenesis (superficial sliding)
b = dermal tectogenesis (deformation of the basement by faulting)
c = bathydermal tectogenesis (plastic deformation of the migmatized zone)
d = subcrustal tectogenesis (hydrodynamic deformation of the substratum)

Bestaat er ook nog andere tectogenese dan gravitatieve ?

ibrium (which is constantly perturbated by differential vertical movements) has not yet been reached.

The regionality of a gravitational stress field is
(1) directly proportional to the deviation of the hydrostatic equilibrium,
(2) directly proportional to the degree of homogeneity of the matter on which the stress field is acting,
(3) limited by the order of magnitude of the threshold values for strength. Local failure will reduce the stress to zero and prevents the stress field from further spreading.

Van Bemmelen (1958) distinguishes stress fields with great, medium, and small regionality which may be superposed on each other.

## I, 7. ENERGY BALANCE.

The gravitational movements obey to the energetic laws. Thus energy cannot be lost. The friction, heat development and deformation and movement of masses during gravitational tectogenesis require energy, which is furnished by the conversion of a part of the potential of the masses involved into other forms of energy (thermal, kinetic).

even then idem up

As the total amount of energy remains the same during the processes it is possible to set up energy balances for the coherent energy systems of shifting masses, if sufficient data about specific densities, volumes, and shifts in position of the rocks are known. The total amount of potential energy decreases during the tectogenesis and it is lost by dissipation in the form of low level thermal energy.

## I, 8. DEFORMATION TYPES OF GRAVITATIONAL TECTOGENESIS AFTER INITIAL GEANTICLINAL UPLIFT.

The tectonic evolution takes place by processes which form a more or less continuous chain reaction, starting with the migration of ions at the one end and the sliding of great parts of the crust (nappes) at the other. A gradual transition occurs between normal erosion (dispersed transport) and gravitational tectonics (non-dispersed transport) as far as quantity of mass involved, velocity and intensity of the processes, and regionality of the stress fields is concerned (see for instance Van Bemmelen, 1952; 1956; 1960, fig. 3 on p. 479, and our fig. 4).

A good classification, description and illustration of the mass transporting processes in the part of the continuous series between erosion and "real" tectonics—involving all kinds of slumping and sliding—has been given in a report by the Committee on landslide investigations, edited by Eckel (1958).

### (8a) Epiderm

The sedimentary epiderm is the zone of the crust with the lowest energetic level and the lowest capacity for stress storage. Thus it will be the first part of the crust to move sidewards by secondary (gravitational) tectonics if a gravitational stress field towards the lower surroundings is created by a vertical uplift. The type of deformation depends on the stress gradient, the existance of lubricating layers, pre-existing shear planes and other anisotropies of the physical properties of the rocks involved. ?

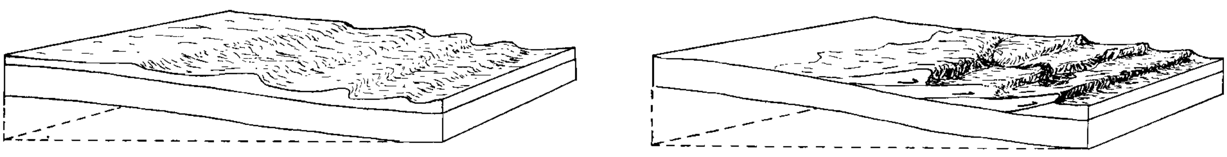


Fig. 5 Gravitative structures in the sedimentary cover (epiderm) of a rising geanticline: a) asymmetric folding, b) décollement and formation of nappes (diverticulation phenomena).

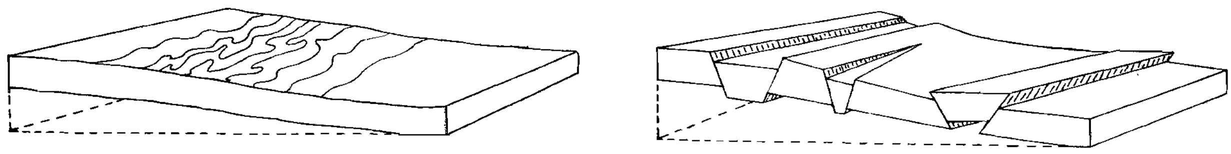


Fig. 6 Gravitative structures in the crystalline basement (mesoderm) of a rising geanticline: a) plastic deformation during the early stages of uplift with steeply inclined fold axes and vortex structures, b) rigid deformation during the later stages of uplift with rifting in the crest and in the flanks and pushing up of wedges in the pressure belt along the foot zones.

Small stress gradients may cause asymmetric folding towards the adjacent lower area with fold axes normal to the regional direction of the topographic slope. Examples are discussed among others by Van Hilten (1960), De Boer (1963), Korn and Martin (1959), and in chapter VI,3. More important movements occur if décollement and sliding of parts or the whole sedimentary cover takes place (fig. 5). Dependent on the scale of the tectonic frame work in which such movements occur the thrust sheets have an area of at most some square kilometers (summit thrusting of the Dolomites, chapter VI, 3; VII, 1; VII, 2); some hundreds of square kilometers (Taio block in the Val di Non area with 160 sq. km. Van Hilten, 1960); or even some thousands of square kilometers (Swiss Helvetian nappes, Northern Limestone Alps). The décollement means tectonic denudation and tension in the high parts of the uplifted area and piling up of strata with compression in the lower parts. This leads to a structural scheme, which is characterized by the fact that the younger strata generally come farther foreward than the older and deeper ones. This principle is known in the german geological literature as "das Voraneilen der jüngeren Schichten" (the precursion of the younger strata). Van Bemmelen (1960) pointed out that this principle is generally valid for the alpine nappe systems. It is a strong indication for the gravitational character of their mechanism of overthrusting. It is an argument against tangential compression, which should be transmitted from the competent crust (mesoderm) to the less competent sedimentary cover (epiderm).

This principle of the glide tectonics may occasionally lead to a reversal of the stratigraphic sequence, if higher stratigraphic units slide down first, to be followed and overridden by the subsequently sliding, later exposed strata ("diverticulation", Lugeon, 1943).

However, there is yet another type of gravity tectonics, which leds to different structural results. When progressive uplift by primary tectogenesis leads to foundering and collapse of the elevated masses and the sidewards squeezing out of more mobile matter at its base, the underlying older strata are squeezed out sidewards. Thus the older and deeper strata advance laterally more than the overlying, subsiding vault. The fault which limits the squeezed out strata at the upper side is called in german "Untervorschiebung" (Kockel, 1957). This principle can be observed in the Pennine nappes as interpreted mechanically by Wenk (1953, 1955) and Van Bemmelen (1960). It is also valid, at a much smaller scale, for the subsidence of the ladino-carnian reef masses in their plastic base, and for the lateral diapirs produced by primary bulges, as described in the chapters VI and VII of this thesis.

### (8b) Mesoderm

The crystalline basement (mesoderm) may pass through a stage of more plastic deformation during the initial slow uplift, when it was still loaded by a thick sedimentary cover. Folding and vortex structures along steep to vertical fold axes, due to the vertical tensional component in the flanks of the uplifted geanticline may occur in this initial stage (see Carey, 1962 b, fig. 41). This may have caused for instance, the steep axes of alpine age in the vortex structure (german; "Schlingen-struktur") at the eastern end of the Schneeberg zone, in the gneisses of the Oetz mass, NW of Merano (fig. 6a).

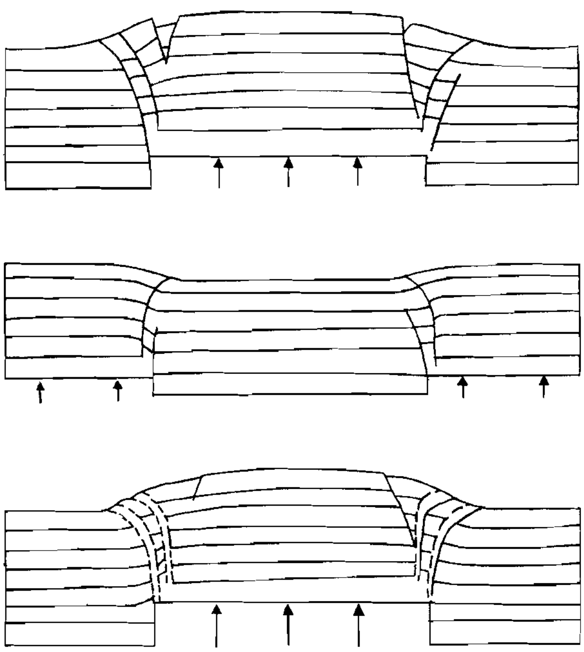


Fig. 7 Scheme of deformations if the lower boundary of a layer undergoes a step in vertical displacement, after Sanford (1959, fig. 18).

This more plastic deformation type is replaced by faulting when the area is still further elevated and the sedimentary cover has been removed by erosion and tectonic denudation (fig. 6 b). The acceleration of the uplift during the later stages of orogenesis promotes also facturing in this stage (see also Carey, 1962 b, p. 132). The crystalline basement occurring in the crest and on the flanks of the uplifted area tends to spread, which may result in a block-faulted basin-and-range structure of the crest, and rifting along normal faults in the flanks (see for instance Van Bemmelen, 1960 a, fig. 5). The lowest part of the slope of the uplifted area is under compression and forms a pressure belt in which wedges of the basement may be pushed up along conjugate faults (see for good examples Korn and Martin, 1959).

The bending over of the upper part of a normal major fault plane and the formation of apparent, steep upthrusts near to the surface has been demonstrated in experiments by Sanford (1959), (fig. 7). Examples in the eastern Alps of this kind are the Pusteria fault and Sugana flexure-fault (Agterberg, 1961); the Bassano flexure-fault (De Boer, 1963); and the Funes fault (chapter VI, 2a).

Large blocks can slide with a backward rotation out of the flank of the uplifted area (fig. 8), showing in principle the phenomenon of slumping by base failure known from soil mechanics. An example is the block of the M. Tullo-M. Putia reef mass sliding together with its basement, discussed in chapter VI, 2a.

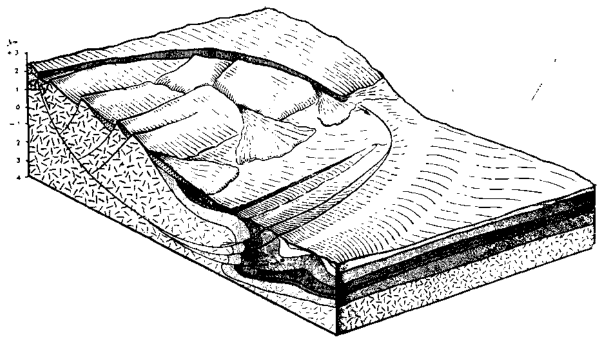


Fig. 8 Rotational slumping movements, after Van Bemmelen (1955, fig. 11). The upper part shows blocks which subside along Y(psilon) faults. The arcuate, tension faults at the top are connected by wrench faults with the imbricated thrust structures in the lower part of the rotating mass.

### (8c) Bathyderm

The mobilized lower part of the crust (bathyderm) with its low specific weight (astenolith), assumed beneath an orogenic uplift, may eventually pierce the crest of the geanticline by its buyoancy and the tensional conditions in the latter. Mantled gneiss domes or granit batholiths result (see also Carey, 1962 b for the movements in the axial zone of orogenes). The magma may intrude moreover along the tensional structures in the flanks of the uplifted area (tonalite intrusions along the Tonale-Judicaria-Pusteria-Drava line, Riesenferner tonalite). See fig. 9.

## I, 9. FOUNDERING AND BUYOANT MASS CIRCUITS INDUCED BY EROSION.

In the foregoing section the tectonics of the structural frame of the Dolomites-block have been discussed. This frame has been structurally influenced by movements of a more extensive (regional) character.

The Dolomites inside this frame had a position which isolated them from the stress gradients of the east alpine geanticline. This protected position was the reason why the sedimentary epiderm of the Dolomites was hardly deformed by regional stress fields. Only during the dissection of this area by cenozoic erosion came a number of more local stress fields of potential energy into existence,

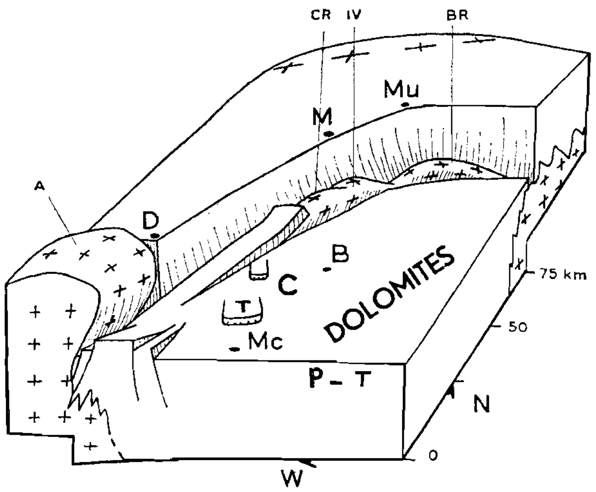



Fig. 9 Intrusions of peri-adriatic tonalites (crosses) along tension structures in the southern flank of the central alpine geanticline, after Van Hilten (1960, fig. 39, c). Vertical scale exaggerated. Adamello (A), M. Croce (Cr), M. Ivigna (Iv), Bressanone (Br), Mules (Mu), Bolzano (B), Dimaro (D), Mezzocorona (Mc), Triassic (Tr), Permian (P), Taio overthrust block (T), Castelfondo overthrust block (C).

causing the local tectonic deformations of the reef complexes, discussed in this thesis.

We will now discuss the mechanics of these local structural deformations in the NW Dolomites. Distinction can be made between two primary structural types:

a) saucer-shaped structures, formed by the foundering of the reef units,
b) dome-shaped and diapiric structures, formed by the squeezing out of the plastic strata at the base of the reefs.

### (a) Saucer-shaped structures

The stability of mass in a vertical sense depends on (1) the type of density layering, and (2) the relation between load pressure, rock strength and possibility of sideward escape, as expounded in chapter I, 5. The situation in the NW Dolomites is schematically represented in fig. 10, a-e (see chapter III for the stratigraphy of the zones in that figure).

The sedimentary column consists of three mechanically different units:

A) A uniform, upper zone being more or less plastic due to its stratification;
B) An intermediate zone with heavy and rigid (reef)bodies, surrounded by incompetent strata;
C) A lower zone with plastic, partly gypsiferous strata.

This initial situation was meta-stable on account of:

1) the presence of a density inversion (dense reefs with spec. weight of 2,5 - 2,7 and low-density gypsum with spec. weight of 2,3), see fig. 10 c,
2) the plasticity and the possibility for sideward escape of the lower zone under the prevailing load pressure, after differential erosion of B. The pressure at the upper boundary of zone C is estimated at 375-500 kg/sq. cm (for a sediment column of 1500-2000 m with a mean spec. weight of 2,5).

The second factor is the most important one for the tectonics of the NW Dolomites.

The overburden pressure is maximal beneath the dense reefs and it causes in the lower zone C the tendency to plastic flow towards the areas with lower load pressure between the reefs. Erosion of part of the rocks of the zones A and of the incompetent rocks of zone B accentuated the differences in load pressure and started the foundering of the heavy (reef)bodies of zone B. The plastic lower series C is squeezed away centrifugally from the high pressure area beneath the heavy blocks of B and it bulges up in domes between the subsiding masses (primary domes). This is Haarmann's principle of "Expressionsgleitung" (Haarmann, 1930; Van Bemmelen, 1931).

Centripetal gliding of matter in the uppermost series A from the domes toward the subsiding areas, closes this flow circuit of masses, which is of the foundering type (see chapter I, 5). The edges of the sinking reef bodies are tilted up by the rise of the squeezed-out matter around. Thus the saucer shape of the subsiding masses resulted.

All movements of sinking, squeezing out, dome-like rising and backflow in the higher level belong to one coherent, local energetic system, driven by gravitative forces. The relatively heavy reefs are comparable to the heavy plunger of a hydraulic press system (chapter I, 5). On a natural, geological scale the saucer-shaped reefs, the domal structures between them, and the summit folding and summit thrusting on top of the reefs are the members of such a hydraulic press system (fig. 10, e). Experiments by Ramberg (1963) show the same phenomena at a laboratory scale (see fig. 10 d).

### (b) Dome-shaped and diapiric structures

These structural forms can be subdivided according to the forces by which they are caused, in:

1) an active type, rising by its own driving force, i.e. the buyoancy of low-density matter,
2) a passive type, driven passively as the volumetrically rising counterpart of an adjacent relatively heavy, foundering (reef)mass.

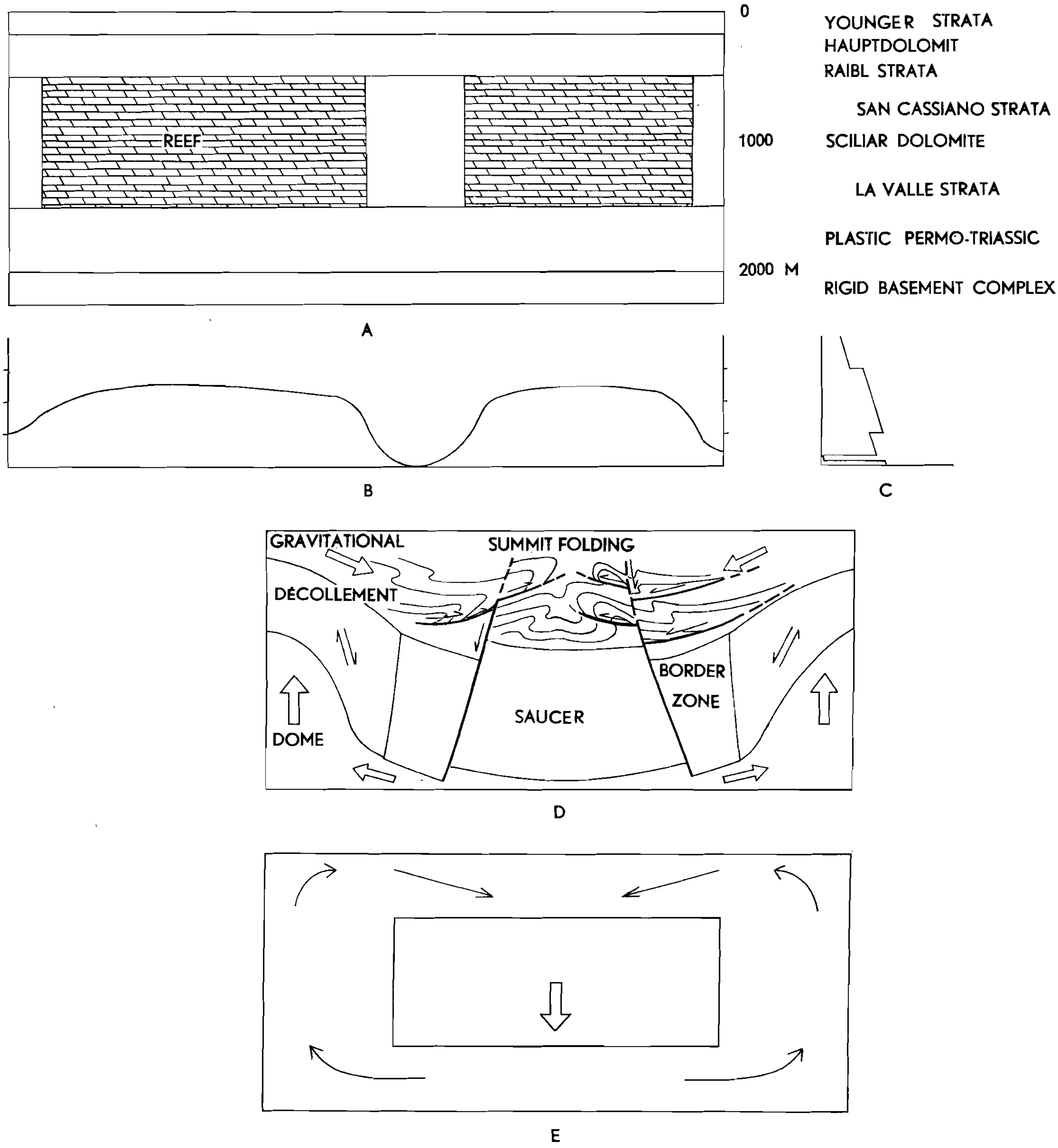



Fig. 10 a) Scheme of the mechanical competency in the sedimentary cover of the NW Dolomites. b) Schematical load pressure curve of zone C. The contrasts are accentuated by differential erosion. c) Scheme of the density stratification in the stratigraphic column of the NW Dolomites. d) Scheme of a foundering circuit, after Ramberg (1963, fig. 46). e) Scheme of the foundering circuits in the NW Dolomites.

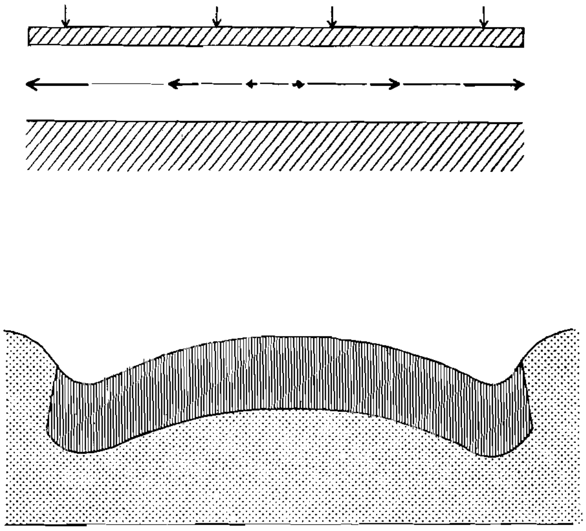


Fig. 11 a) Stiff plate pressed down on plastic mass, after Ramberg (1963, fig. 20). b) Profile of a viscous layer which flows out underneath the load of a layer of plastic material, after Ramberg (1963, fig. 22).

Although the driving force is inside and outside the structure respectively, both types can have the same structural behaviour and appearance.

The primary domes between the heavy reef bodies of the NW Dolomites (such as the Campolongo and Buffaure domes, see chapters VII, 5 and VII, 4) belong to the passive type. They were formed in the depressions, cut in the more erosible strata between the reefs.

In one case, however, the passive type of doming affected a reef plate: the Marmolada mass. Ramberg (1963), from his experiments with a foundering plate deduced from his experiment with a foundering plate deduced the distribution of the vertical stress component beneath it and the resulting form (fig. 11).

The heavy loads adapt themselves by sagging, till their load can be supported by the layers below. As a border effect the edges of the saucer- and dome-structures are dragged up. If the border zone consists of rigid rocks, these are faulted and the blocks rotate with a backward rotation towards the centre of the subsiding plunger.

In the experiments of Ramberg the location of passive marginal domes was related to changes in the amount of overburden (fig. 12).
The same was observed in the natural case of the Sasso Lungo reef (see chapter VII, 3 and fig. 41). This reef mass was too small (area of about 8 à 9 sq. km) to push up large primary domes but instead of it a diapiric fringe was formed at its base along the NW and N side.

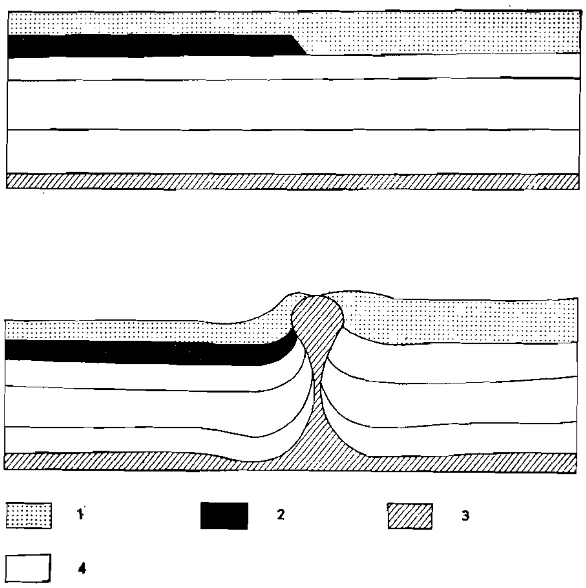
Dome-shaped structures start as flat bulges (non-piercement stage) and may gradually evolve into diapirs (piercement stage), passing through all stages of development (see for instance: Trusheim, 1961; Carey, 1962 b; Ramberg, 1963, and fig. 13). The shape and dimensions of such domal and diapiric structures depend on:

1) The physical properties of the intruding mass and of the enveloping country rock (competency, density, type or absence of stratification).
2) The intensity of the local stress fields and the interaction with stress fields of greater regionality.
3) The available volume of intruding matter.

Processes of doming and diapirism (in a broad sense) may affect sedimentary as well as magmatic matter, ad they may occur at a local, as well as a geotectonic scale. The rising movements in dome-shaped and diapiric structures are caused by differences in potential energy of masses and the tendency to acquire a stable situation (hydrostatic equilibrium); energy balances can be drawn for the individual cases (Van Bemmelen, 1958).

The structural evolution of the Marmolada bulge (Chapter VII, 7) shows a close similarity with one of Ramberg's experiments, in which the non-piercement stage was followed by piercement and collapse. All structural elements of the Marmolada group are found in the experiment, though strongly exaggerated in form on account of differences in

Fig. 12 a) Sketch of initial arrangement in model experiment of Ramberg (1963, fig. 35). b) Development of a diapiric zone where the amount of overburden changes in Ramberg's experiment (1963, fig. 37) 1. powdered wax 2. olivine powder 3. stitching wax 4. painter's putty with marker layers. Diameter of model 94 mm.



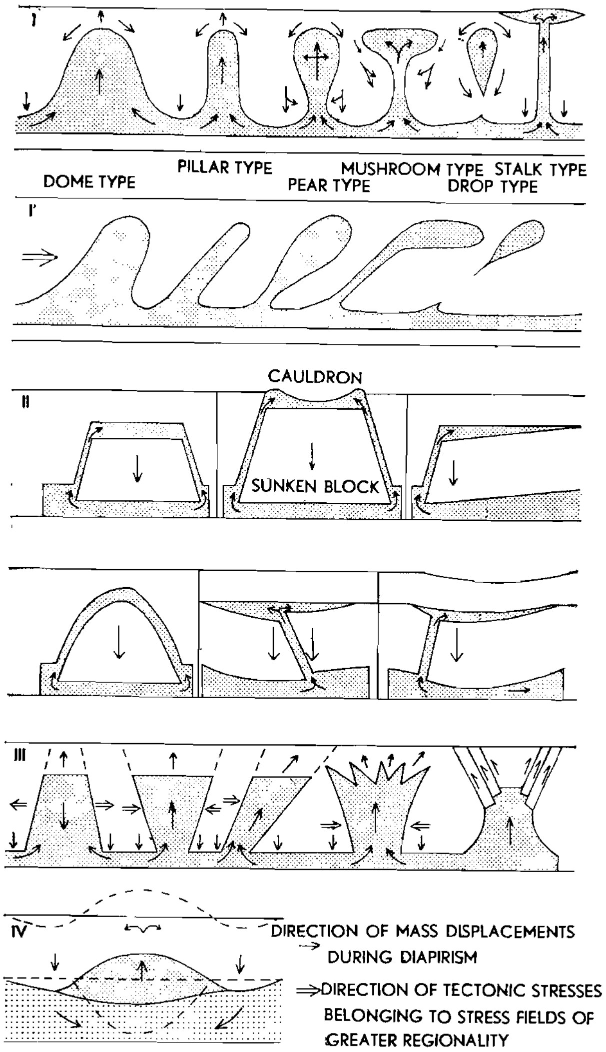



Fig. 13 Stages of diapirism, after Van Bemmelen (unpublished report).

plasticity between model and nature. See for comparison fig. 14 and the section of fig. 54 with its northward directed Soura Sass anticline, the diapiric central zone with southward upthrusting, and the southward imbricated limb.

## I, 10. THE TYPE OF DEFORMATION IN RELATION WITH THE AREA OF THE FOUNDERING MASS.

A relation seems to exist between the area of the subsiding plunger body and the type of deformation it will undergo when settling in a plastic base. Three types of deformation were observed in the central NW Dolomites:

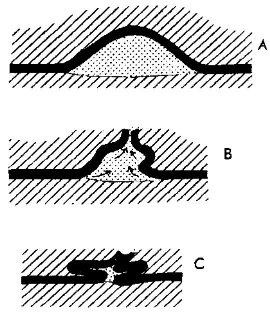



Fig. 14 Sketch of non-piercement doming and subsequent collapse along vent in an experiment of Ramberg (1963, fig. 41).

a) a small rigid unit (Sasso Lungo, 3 x 3 sq. km) falls apart in blocks;
b) rigid units with intermediate area (Sella, 7 x 6 sq. km; Puez-Gardenaccia, 10 x 7 sq. km) assume a saucer shape;
c) the largest rigid unit (Marmolada complex, 8 x 12 sq. km) assumes a dome shape and is diapirically pierced later on.

The radius of action of the border effect of rotational block movement (discussed in one of the preceding paragraphs) might give an explanation for the observed differences in behaviour of otherwise comparable reef masses. The width of the rotating border zone depends on the magnitude of the density differences, the thickness and the rigidity if the strata, and the depth of erosion. This border zone will have a mean width if the conditions are more or less identical.

For the reef groups in the NW Dolomites the actual width of this border zone seems to be about 1000 m, that is about as wide as the thickness of the reef plates.

The border effects at both sides will mutually interfere if the subsiding central mass has a diameter which is less than twice the radius of action of the border zone. The result will be a deformation of the reef mass by faulting, so that it falls apart into small blocks. The Sasso Lungo is a good example (see fig. 40). When the subsiding mass is somewhat larger than twice the radius of the border effect (case b), the border effect will still dominate the whole deformation pattern of the subsiding mass, so that a saucer shape is the resulting form (Sella, Puez-Gardenaccia, Fanes). If, however, the diameter of the subsiding reef mass is much larger than twice the radius of the dragged border, the mass will have a dome-shaped centre, surrounded by upward tilted edges (Marmolada).

## I, 11. SMALL GRAVITATIVE EFFECTS ALONG VERTICAL STEPS IN TOPOGRAPHY.

The tendency to hydrostatical equilibrium of masses and the reduction of their potential energy causes tension in the topographic, higher parts and compression in the depressions.

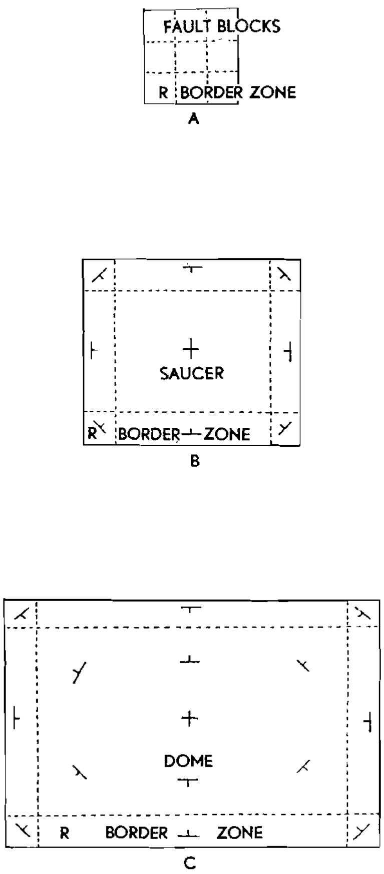



Fig. 15 The relation between the type of deformation of a subsiding reef mass in the NW Dolomites, its area, and the radius of action (R) of the border effect (tilted zone) a) faulting if the diameter of the reef < 2 R, b) saucer shape if the diameter of the reef > 2 R, and c) dome shape if the diameter of the reef » 2 R.

The carve of a valley in the rocks forms a zone of minimal potential energy and consequently migrations of mass towards it will tend to take place. This migration occurs in the dispersed form of mechanical and chemical erosion and deposition and in non-dispersed form by gravity tectonics with stretching, faulting, folding, and thrusting. Plastic layers may be squeezed out laterally towards the valleys under their overburden as discussed in chapter I, 5. An example is the "line of Gardena" in the Gardena Valley (see chapter VI, 2, d). The squeezed-out layers form in other cases small, second order, lateral diapirs around the first order, vertical domes of the NW Dolomites. These domes were pushed up by the subsiding reef masses and are surrounded by deep valleys.

The lateral diapirism along valleys is related to the stages of valley carving. It follows the old levels of the river (terraces) and migrates to a deeper zone when a younger and deeper valley floor — acting as a local base level for diapirism — develops. The older and higher lateral diapiric zone then becomes inactive (fig. 16, a).

The valley bottom is under vertically upward stress (see fig. 16, b) and may bulge up locally or even over great distances along the river course forming a complete anticline (for instance in the upper Cordevole Valley; chapter VII, 6 and VI, 4). Hollingworth et al. (1944) gave similar examples for Northampton.

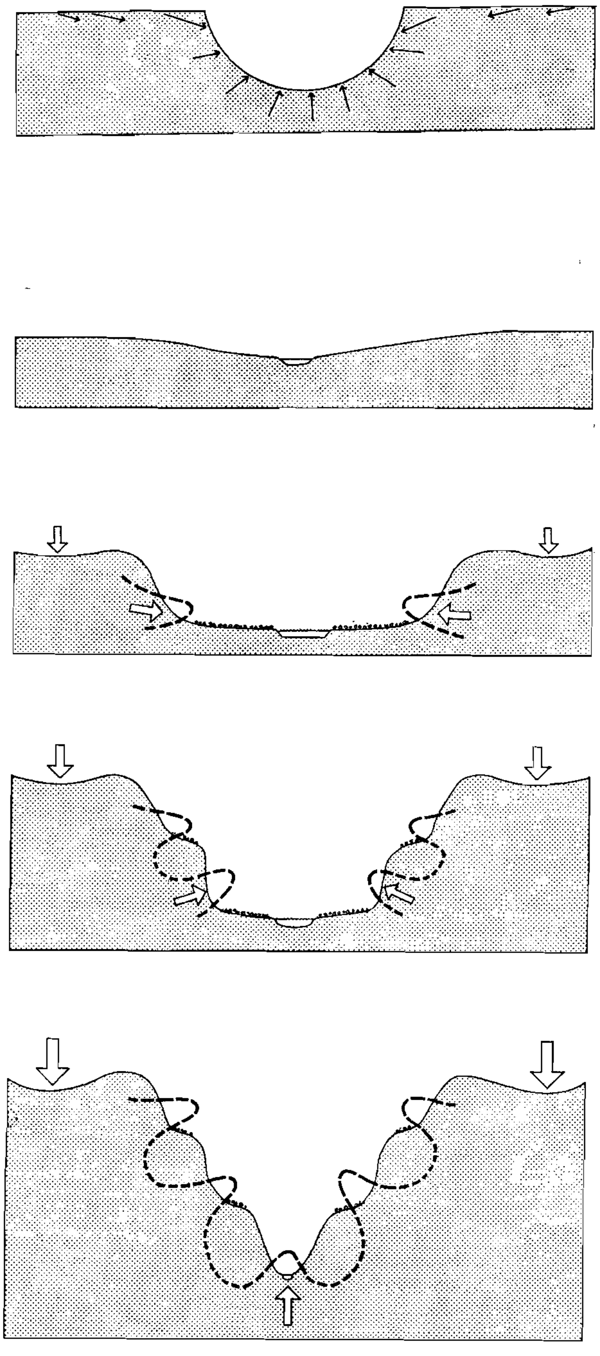


Fig. 16 a) Profile across a depression in a plastic body. Arrows indicate the direction and the relative rate of flow, after Ramberg (1963, fig. 47).
b) Scheme of lateral diapirism and anticlinal bulging-up of the valley floor, related with stages of incision of the river.

# CHAPTER II

# DISCUSSION OF THE GEOLOGICAL LITERATURE CONCERNING THE NW DOLOMITES

## II, 1. THE FIRST PERIOD OF GEOLOGICAL RECONNAISSANCE.

The Dolomites are one of the most thoroughly investigated areas of the alpine mountain range. The oldest geological observations have been recorded in a poem of 1558.

The rich mineral associations of the volcanic triassic rocks soon directed the attention of mineral collectors to this area and stimulated geological investigations.

Von Klebelsberg (1935) compiled a summary of the numerous papers concerning the region of Tirol (of which the NW Dolomites are a part) for the period from 1558-1935. Two important publications in the second half of the nineteenth century contain almost all information previously gathered, together with the results of the elaborate studies of the authors themselves. These publications are: "Die geognostische Beschreibung der Umgebend von Predazzo, Sanct Cassian und der Seiser Alpe" (Ferdinand, Freiherr von Richthofen, 1860) and "Die Dolomit-Riffe von Südtirol und Venetien, Beiträge zur Bildungsgeschichte der Alpen" (E. Mojsisovics von Mojsvàr, Vienna, 1879); the latter monograph was accompanied by a geological map in six sheets on a scale 1:75.000. The prevailing opinion on the tectonics of the NW Dolomites in this period was, that the main tectonic features were normal faults. This synthesis by Mojsisovics terminated the first period of geological research in the NW Dolomites.

## II, 2. THE PERIOD OF DETAILED GEOLOGICAL SURVEY.

In the period of about 1880-1935 the knowledge of tectonics, stratigraphy, paleontology etc. of the Dolomites area was worked up in more detail by many geologists. A noteworthy volume on the Marmolada group was published by Salomon (1895). In this period the NW Dolomites were covered by a series of geological maps on the scale 1 : 25.000, made by Mutschlechner, Reithofer and others of the geological institutes of the austrian universities of Innsbruck and Vienna. The english female geologist Mrs. Ogilvie Gordon also devoted a good deal of attention to this area for many years.

In 1900 Diener was the first to suggest that the intense deformation in the plastic permo-triassic strata beneath and around the ladino-carnian reef masses were the result of the subsidence of the latter into their plastic base. However, his view was almost unanimously rejected by the other geologists working during this period in the NW Dolomites, because they were too much influenced by Suess's attractive hypothesis of alpine mountain building by means of tangential compression.

Ogilvie Gordon, for instance, initially tried to unravel the tectonics of the NW Dolomites by assuming many superposed nappes. Although she soon abandoned the idea, she adhered to the concept of general compression. Such an alpine compression acting from diverse directions, should have caused a complicated system of "torsion structures". Ogilvie Gordon has contributed greatly to the present knowledge of the concerned area, even though her concepts on the tectonic development were not supported by later geological investigations. The same can be said of the very valuable monographs on the individual mountain groups of the NW Dolomites produced by the austrian school of geologists. These studies — which formed a reliable base for our work — started from a general compression from S to N, causing N-ward movements. In these monographic studies the chapters on the tectonics were still mainly descriptive. The southern part of the Dolomites was mapped in this period by Vardabasso an others of the university of Padova.

Von Klebelsberg's classical volume: "Geologie von Tirol" summarizes all knowledge concerning the Dolomites up to 1935; it contains a wealth of information and a very extensive list of literature.

## II, 3. THE PERIOD OF STUDYING SPECIAL PROBLEMS OF FACIES, PALEONTOLOGY AND TECTONICS.

The importance of italian geological research in the NW Dolomites became predominant in the third period, from 1935 up to the present time. The investigations are mainly carried out by members of the universities of Ferrara and Padova, among whom Prof. Piero Leonardi of Ferrara has contributed most papers. Together with his pupils he investigated among other things, the facies development of the ladino-carnian reefs, paleontological problems and areas with complicated tectonics.

Leonardi considers the tectonics of the Dolomites primarily as the result of tertiary, tangential compression related with the alpine mountain building. In the Dolomites these orogenic forces should have formed a synclinorium with E-W and NE-SW trending folds, which are asymmetric or overturned to the south. The fold axes converge eastward. Gravity tectonics is given but a limited role by this author, it should account only for the explanation of the complicated minor tectonic phenomena on the higher parts of the dolomite masses (summit foldings and summit thrusts). These phenomena were thoroughly investigated by Accordi (1955, a 1957), who established their gravitative origin.

The intricate intermingling of sedimentary and volcanic triassic rocks along the Fassa and Cordevole Valleys is interpreted by Leonardi as the effect of volcano-tectonic processes of triassic age. The synthetical, well-illustrated study of Leonardi: "Breve sintesi geologica delle Dolomiti occidentali" (1955, a) contains the gain in knowledge in the period after 1935, and has a comprehensive list of the literature.

In 1950 the french geologist Fallot suggested a gravitative décollement of higher parts of the sedimentary epiderm. Also Signorini (1951, 1955) showed that the tectonics of the NE Dolomites might be explained more satisfactorily by refraining from the concept of orogenetic, tangential compression, and by attributing a dominant role to gravity tectonics.

## II, 4. THE PERIOD OF THE TECTONIC RESEARCH IN THE EASTERN ALPS BY THE UTRECHT GEOLOGISTS.

An extensive research program has been carried out since 1955 in the eastern Alps by students of the Geological Institute of the State University of Utrecht (Netherlands) under the supervision of Prof. Dr. R. W. van Bemmelen, according to the latter's concepts on east alpine mountain building (see for instance Van Bemmelen 1960 a, and 1960 b).

The Alps are a geanticline which has been domed up since the early Tertiary by a buyoant root of granitic magma (asthenolith). This updoming (primary tectogenesis) initiated secondary gravitative reactions (secondary tectogenesis). The periadriatic line separates the central alpine uplift from the southern Alps (Dinaric branch), (see also chapter V). This fault line is composed of the Insubric-Judicaria-Pusteria-Drava fault system, which was formerly considered as a root zone of the alpine nappes. Van Bemmelen's studies (1957, 1961) on the Gailtal Alps along the Drava line ("Drauline"), and the theses of Dietzel (1960), Van Hilten (1960), and Agterberg (1961) have shown that this suture line is a tertiary system of normal faults with great vertical throw (5-9 km) accompanied by minor antithetic and synthetic faults. Moreover, Van Hilten proved the gravitative character of the structures of the Val-di-Non area.

Agterberg made a study of the crystalline basement complex of the Dolomites (the mesoderm of the crust) by means of a statistical analysis of minor tectonic features. Our investigation is largely concerned with the tectonics of the sedimentary cover of the Dolomites (the epiderm of the crust). An explanation by means of gravity tectonics is proposed. De Boer (1963), who studied the Vicentinian Alps south of the Dolomites, came to similar results. Theses by R. Guicherit on the eastern Carnian Alps, and by S. Pieplenbosch on the Val Sugana are in preparation, all arriving at an interpretation of the tectonic structures as gravitational reactions to local accumulations of potential energy. These doctoral theses of the State University of Utrecht are based on the extensive stratigraphic and tectonic knowledge, gathered by previous generations of geologists. The additional investigations by the authors of these theses confirm the validity of the concepts of gravity tectonics and their application to east alpine mountain building, as was suggested by Van Bemmelen (1960, a).

The theses of Dietzel (1960), Van Hilten (1960), De Boer (1963), Guicherit (1964, in preparation), and Pieplenbosch (in preparation) are, moreover, partly dedicated to the study of paleomagnetism in the southeastern Alps. These studies belong to the research program on european paleomagnetism carried out by the Geological and Geophysical Institutes of the university of Utrecht. Investigations on this subject for areas outside the eastern Alps were published by: Rutten, Van Everdingen and Zijderveld (1957), As and Zijderveld (1958), Van Everdingen (1960), Nijenhuis (1960), Van der Lingen (1960), Van Hilten (1961, 1962), Kruseman (1962), and Schwarz (1962).

For the Dolomites under discussion here, these theses suggest large scale translations and rotations of the Dolomites in permomesozoic time (see especially De Boer, 1963). This leads to a mobilistic concept for the pre-tertiary geotectonics of this part of the Alps.

On the other hand, our thesis, discussing the tertiary tectonics of the Dolomites, leads to a strictly fixistic picture of the mechanics of the tectogenesis. These two views do not exclude each other. They are complementary to one another, as has recently been expounded by Van Bemmelen (1963), who proposes a "relativistic" concept of geotectonic evolution.

# CHAPTER III

# STRATIGRAPHY

## III, 1. CONCISE DESCRIPTION OF THE STRATIGRAPHIC COLUMN.

The stratigraphy is discussed only shortly because we may refer to the many excellent papers concerning the subject. The reader will find more data and literature references for instance in the publications of Von Klebelsberg (1935), Leonardi (1955 a, 1961), Leonardi and Rossi (1957), Dietzel (1960), Van Hilten (1960), Agterberg (1961), Sacerdoti and Somavilla (1962), Mittempergher (1962), and De Boer (1963).

## THE CRYSTALLINE BASEMENT COMPLEX (CRUST, OR MESODERM)

### The Quartz phyllite series

The basement of the Dolomites consists of epi to mesometamorphic, fine to medium-grained quartz phyllites. The phyllites — rich in quartz veins — are locally intercalated with carboniferous quartzites, green phyllites, saccharoidal limestones, gneisses, and phacoidal gneisses. The strata were already deformed during the hercynian orogeny and are cut by an erosion surface, which was the plane of deposition for locally developed conglomerates at the base of the Permian. The age of the quartz-phyllitic complex is uncertain. Very scarce graptolites seem to indicate a silurian age, but this is not generally accepted and the rocks may even be older. More data about the basement complex and literature references are given in the theses of Agterberg (1961) and De Boer (1963).

## THE SEDIMENTARY EPIDERM

## PERMIAN

### The Basal series (Lower Permian)

The Basal series is composed of locally developed, terrestrial, fluvial strata, which were unconformably deposited in topographic depressions of the basement complex. Pebbles of quartz and quartz phyllites — both erosion products of the hercynian mountain range — are the main components of the gray-greenish, seldom reddish breccias and conglomerates. A maximum thickness of about 100 m occurs, but in other places the Basal series is absent. In places alternations with volcanic tuffs, tuff-breccias and lava flows indicate the beginning of the permian volcanism.

### The Effusive system

This series is made up by a pile of ignimbritic lava flows, interbedded with tuffs. The ignimbritic character of the permian volcanic rocks in the sequence of quartz porphyries in the Bolzano district was at first recognized by Mittempergher (1958). The lower flows have filled the existing topographic depressions and have a discontinuous distribution. The higher flows are more widespread over the surface which had been smoothed by the preceding flows. The total thickness of the series ranges from zero to more than 1000 m. A lower, more basic series of quartz latites and rhyolites, trachy-andesitic tuffs and lavas, and an upper more acid series of quartz latites and rhyolites are distinguished. The quartz porphyries have a lower permian age. Details about texture and composition of the red and green-coloured porphyries and literature references are given by Mittempergher (1962).

### The Gardena formation (Middle Permian)

On top of the permian effusive rocks — or when absent, as along the NW border of the Dolomites, immediately upon the quartz phyllites — the clastic Gardena formation of 100-250 m thickness was deposited. It is composed of coarse, continental, feldspatic sandstones with red, but locally greenish or greyish colours. The sandstones grade in the higher levels into red pelites and dolomitic and gypsiferous layers, which form the transition to the upper permian Bellerophon formation. Sporadically thin coal seams occur. A small marine intercalation with nautiloids and ammonites has been described. Plant remains and foot prints of amphibians and reptiles point to the terrestrial character of the formation; the marine interruption indicates a near-shore deposition.

### The Bellerophon formation (Upper Permian)

The lower part of this formation consists of evaporites. The gypsum and gypsiferous marls are separated from the upper series of bedded bituminous and oölitic limestones by cellular dolomites ("Rauhwackes"). The succession shows the transgression of the triassic sea over the continental, middle permian Gardena sandstones. The thickness may reach a maximum of 200 m in the central Dolomites and decreases to zero in the Bergamasc Alps. Exact determinations of the thickness are difficult because the Bellerophon strata are often strongly deformed. Calcareous algae are frequent, the gasteropod Bellerophon, giving the formation its name, is rare (Leonardi, 1955 a, p. 14).

## TRIASSIC

### The Werfen formation (Skythian, Lower Triassic)

The Werfenian is a marine series of finely clastic, near-shore deposits: calcareous sandstones and shales with (in the middle of the formation) some beds of oölitic limestones. The thickness ranges from 200 to 420 m but is in most cases influenced by tectonic processes. A division in an upper and lower part of the series has been made. The underlying calcareous Bellerophon strata gradually pass into the lower Werfenian, called the strata of Siusi ("Seiser Schichten"). The alternation of mostly yellow and greyish shales and calcareous sandstones is followed by some oölitic limestone beds with small gasteropods ("Gasteropodenoölit"). Locally the oölites are accompanied by conglomerates (conglomerate of Koken). The upper Werfenian, the strata of Campil ("Campiller Schichten"), greatly resemble the strata of Siusi, but they are somewhat coarser and contain more mica flakes on the bedding planes. Their colour is generally reddish-violet, though thin brown and yellowish-grey beds occur. In the field a lithological distinction can be made between the strata of Siusi with grey and yellowish brown colours and the strata of Campil with a predominantly reddish tint. Contradictory opinions on the prevalence of the red colour in the strata of Campil seems to be mainly the result of confusion through perturbations and mixing of the stratigraphic sequence by the frequent plastic deformations in the Werfenian. The badly preserved bivalves in the formation are rich in number but they belong to a few species only.

### Anisian (Middle Triassic)

The lower anisian series is marly and calcareous, the upper Anisian is dolomitic. The lower anisian strata at the base of the Lower Triassic have often the same appearance as the upper part of the Werfenian. The clastic strata of Campil pass gradually into the more calcareous Anisian. A conglomerate with maximal thickness of 8 m — called the conglomerate of Richthofen — forms, if present, a clear lithologic boundary between the Werfenian and the Anisian. In the Anisian changes of facies and thickness are frequent and occur within short distances.

The middle and upper Anisian consists of a white or yellowish, massive dolomite of varying thickness. In older publications, the dolomite was called Mendola dolomite ("Mendeldolomit"), but it is described in the last decades under the name of Serla dolomite ("Sarldolomit"). In the Marmolada group the massive limestone of Contrin replaces the Serla dolomite. The thickness ranges from zero to 200 m.

The uppermost part of the Anisian is a thin series of bituminous limestones (Trinodosus strata) which are found only locally.

### Ladinian (Upper Triassic)

The rocks of ladinian and lower carnian age show two coexistant and laterally interfingering facies types. Organogenic dolomitic reef masses (bioherms) grew up in the triassic sea, whereas at the same time clastic volcanics and effusives, interbedded with normal sedimentary marine strata were deposited in the sea between the reef islands.

### Livinalongo strata ("Buchensteiner Schichten")

The lower Ladinian is formed by the Livinalongo strata: marly limestones with silicious nodules ("Knollenkalke") and thinly laminated, blackish, silicious limestones ("Bänderkalke") with finegrained, green tuffites ("Pietra verde"). The eruption centres of these tuffites were south of the Dolomites. The thickness of the formation ranges from zero to 1900 m. In some reef groups the Livinalongo strata probably developed in a dolomitic facies and the sole indication of their location is a diastem between the underlying Serla dolomite and the overlying Sciliar dolomite.

### La Valle strata ("Wengener Schichten")

The triassic volcanism comes to full development in the northwestern Dolomites in upper ladinian time. The La Valle strata are an alternation of stratified, marly tuffites, agglomerates, pillow-lavas, pillow-breccias, hyaloclastics and marly limestones. A part of the La Valle strata is formed by the monotonous series of yellowish, marly and calcareous material alternating with brownish tuffaceous strata.
This facies type is known in the italian literature as the "ladinian flysch". The submarine effusions of basic augite-porphyritic lavas took place most probably along NW-SE trending fissure systems. The huge blocks of older, sedimentary material which are found irregularly distributed in zones in the volcanic series, were interpreted by italian investigators as volcano-tectonic breccias, caused by violent explosions. However, they appear to be the outcrops of later tertiary and quaternary diapir structures, piercing the volcanic strata (see chapters VII, 3; VII, 4, and VII, 5).

### San Cassiano strata ("Cassianer Schichten")

The basal part of the lower and middle carnian San Cassiano strata is lithologically merely the continuation of the La Valle strata. No clear boundary between the two formations occurs. The San Cassiano strata are built up by the multi-coloured alternation of thinly bedded limestones, marls and tuffaceous sandstones and shales with a rich dwarf fauna. Along the facies boundaries with the surrounding reefs large blocks of reef limestone and dolomite occur within the strata.

These blocks, which may have a diameter of some meters, are called Cipit limestones. They were isolated coral colonies near the main reef mass or erosion products which tumbled down the nearby submarine outward slope of the reef. The total thickness of the La Valle and San Cassiano strata together is about 1000-1100 m.

### Raibl strata ("Raibler Schichten")

The upper carnian Raibl strata consist of a series of marls and limestones, locally dolomitic or gypsiferous, maximal 50 m in thickness. The Raibl strata mark the end of the vertical growth of the ladino-carnian reefs, which are capped by them. The Raibl strata may become dolomitic towards the centre of some reefs, which makes it hard to separate them from their base of Sciliar dolomite or the overlying Hauptdolomit. The argillaceous, easily erosible Raibl strata are exposed in a flatter, topographic fringe between the vertical walls of the Sciliar dolomite and the steep scarps of the norian dolomites.

### Sciliar dolomite, and Marmolada and Latemar limestone ("Schlerndolomit")

The ladino-carnian Sciliar dolomite is a massive, white or rose coloured, in places reddish to grey coloured dolomite. The reefs are accumulations of organogene material, such as corals, molluscs, and calcareous algae. Leonardi et al. elaborated the distinction in various types of reef development which were already recognized by Mojsisovics (1879). The former carefully investigated the relations between primary inclined, clastic fore reef deposits ("Uebergussschichtung"), massive reef dolomite and stratified lagoon dolomites (back reef facies) in the centre of some of the reef groups (see among others: Leonardi, 1955, 1961; Leonardi and Rossi, 1957).

Good examples of the interfingering by lateral changes of facies between the reefs and the surrounding La Valle and San Cassiano strata are visible at the western side of the Sella group. The thickness of the Sciliar dolomite reaches a maximum of 1000-1100 m between the Livinalongo and Raibl strata, but in many cases the isochronous La Valle and San Cassiano strata will replace the outer parts of the reef in the periods of impeded reef growth due to the influences of the volcanic activity. Some smaller, isolated reefs were completely killed and covered by La Valle and San Cassiano strata.

The reefs of the Marmolada and Latemar groups are composed of unaltered limestone, but in other respects they are comparable to the other reef groups, which were subsequently dolomitized.

### Hauptdolomit (Norian)

The norian Hauptdolomit was formerly described under the name "Dachstein-dolomit". This formation consists of regularly stratified, compact, white dolomite which has a great distribution. The thickness of 200 - 400 m in the NW Dolomites increases eastward. The Norian is found in the same facies in the entire area of the Dolomites. This shows that the pronounced facies heteropy of the Ladinian, which was already covered by the also widely distributed Raibl strata, had definitely come to an end. Occasionally the large shells of Megalodon are conspicuous fossils in the norian dolomites.

## JURASSIC

Few relics of jurassic strata were preserved in the NW Dolomites, the total thickness will not exceed 50 m. The Liassic consists of grey limestones, which are found on the top plateau of the Sella group.

The Dogger is represented in transgressive facies over the Norian of the Puez group, where the Liassic is absent. A basal conglomerate is followed by 2-7 m of glauconitic dolomite and 2-3 m of white or reddish limestones, rich in crinoids and brachiopods. The top of the series is composed of maximal 20 m of red, nodular, marly limestones with ammonites ("Acanthicus Schichten", "Rosso Ammonitico").

The Tithonian is probably represented by thinly bedded greyish and red, marly limestones with silica nodules.

## CRETACEOUS

The tithonian limestones pass without any lithological change into the Lower Cretaceous (Neocomian), so that no precise boundary can be given. The series of marly limestones with silica nodules is at most 100 m thick and contains also some less important grey and greenish marls and black marls and limestones.

Small remnants of a thin sheet of breccias and conglomerates were preserved through their low structural position on the top of the subsided Sella group. The deposit consists of breccias of upper jurassic and lower cretaceous rocks (Reithofer, 1928 b, p. 555). Moreover, polished and well-rounded dolomitic pebbles with a diameter of 0,75 cm and small, translucent quartz pebbles were found. The marly matrix contains many limonitic concretions (bean iron ore). These young mesozoic deposits were folded during the oligo-miocene summit thrusting on the Sella group (see chapter VII, 2).

## TERTIARY

No tertiary sediments seem to be present in the NW Dolomites except for some fluviatile gravels in the Buffaure area east of the Fassa Valley, which are probably of late-tertiary age. The tertiary strata in the Val-di-Non and Brenta areas, west of the Dolomites, are discussed by Van Hilten (1960) and others.

## QUATERNARY

The Quaternary of the NW Dolomites consists of glacial deposits, fluviatile accumulations and screes along the foot of scarps.

## III, 2. SIGNIFICANCE OF THE PHYSICAL PROPERTIES OF THE SEDIMENTS AND THE FACIES HETEROPY FOR THE TECTONIC DEVELOPMENT.

The deposition of gypsum and gypsiferous marls in the Bellerophon formation at the base of the stratigraphic column represents an anomaly in a stable density stratification. The low specific weight and the plasticity promoted their later diapiric movements and their function as lubricating horizons for sliding movements.
The vertical succession in the formations from the permian Gardena sandstones to the upper anisian Serla dolomite has the same facies over a fairly wide area, so that in the NW Dolomites the physical properties of the strata at the base of the ladinian series are more or less the same. The facies heteropy of the Ladinian caused strong variations of the physical rock properties in a lateral sense. The ladino-carnian reefs form in the NW Dolomites massive, isolated groups of bioherms, surrounded by valleys which were eroded in marls, tuffs, and lavas of the La Valle and San Cassiano strata.

The primary differences of facies are decisive for the way in which the area was eroded and for the origin of the gravity tectonics related to this erosion. The different physical characteristics for the reef sections and the sections with sedimentary and volcanic strata between the reefs may be summarized as follows:

| reef section | sedimentary - volcanic section |
|---|---|
| 1. resistant to erosion | 1. easily erosible |
| 2. mainly rigid and competent | 2. mainly plastic |
| 3. faulting predominates | 3. folding predominates |
| 4. mean spec. weight 2,6-2,7 | 4. mean spec. weight 2,3-2,5 |
| 5. structural "lows" are at present topographic "highs" | 5. structural "highs" are at present topographic "lows" |

The rather well-bedded and uniformly distributed Raibl, Hauptdolomit and younger formations formed a cover of uniform facies, extending over the ladino-carnian series.

Consequently, the stratigraphic column shows a division in three levels of different structural behaviour ("Stockwerke"):

A) The lower zone of upper permian and lower triassic plastic rocks partly of relatively lower density, which causes a meta-stable density stratification.

B) The middle zone of ladino-carnian rocks with strong variations in density and competency in a lateral sense.

C) The upper zone of upper triassic and younger rocks, which are less competent due to their good stratification and which are lubricated by the marly and gypsiferous Raibl strata at their base.

The gravity tectonics were set in motion by the combination of movements of the basement and the trigger action of the erosion. The settling of the reef masses (B) in their plastic base of permotriassic rocks (A) was promoted by the presence of the plastic matter in the lower "Stockwerk". The gravitative reactions of the upper zone (C) to the interplay of the tectonics in the lower and middle zones (A and B) caused the summit thrusts and summit foldings ("Gipfel-überschiebungen" and "Gipfelfaltungen").

# CHAPTER IV

# THE MORPHOLOGIC DEVELOPMENT IN CENOZOIC TIME

## IV, 1. SUMMARY OF THE MORPHOLOGIC DEVELOPMENT.

The morphologic development of the NW Dolomites shows the close interaction between tectonical and erosional processes. Climatic changes, chemical and physical properties of the rocks in the stratigraphic column, and lateral changes of the facies are important factors in this history.

A landscape of great beauty was modelled in the following stages since the lower Tertiary:

1) The area was truncated by an extensive erosion level of oligo-miocene age (Chattian-Aquitanian) after a first phase of uplift of the alpine geanticline in the lower Tertiary (first altiplanation).
2) A second phase of uplift during the Miocene and lower Pliocene caused a dissection by a mainly vertical fluviatile erosion of about 1000 m.
3) A renewed truncation of the area occurred in the upper Pliocene (second altiplanation). This erosion surface, the "Tre Passi" level, is especially well developed in the less resistant middle-triassic strata around the reef masses, though it is also found in the Norian and the belt of quartz phyllites along the northern border of the NW Dolomites. The present altitude ranges from 1900-2300 m.
4) A third phase of uplift occurred in the upper Pliocene and the Quaternary. This caused a renewed vertical dissection by mainly fluviatile erosion of 1000-1500 m. The pleistocene glaciations modelled minor forms in the area.

A storeyed lanscape resulted from these morphogenetic stages in the NW Dolomites (see graph, fig. 17).

## IV, 2. DISCUSSION OF THE EROSION SURFACES.

Rossi (1957) studied the relics of the oldest erosion surfaces in the NW Dolomites and reviewed the existing literature on the subject. We fully agree with his conclusions that an oligocene-miocene erosion surface is present, which was subsequently warped and overthrust by the gravitational summit thrusts (for instance in the Sella group).

The initial altitude above sea-level of the oligocene erosion surface cannot be determined, on account of the younger vertical movements of the entire Dolomites together with the rising alpine geanticline. The "original" vertical distance between this oligo-miocene surface and the late pliocene erosion level can be measured by comparing the actual difference in altitude between tectonically undisturbed relics of both surfaces. The summit level at the west side of the Catinaccio group (Catinaccio d'Antermoia, 3004 m) seems to approach the requirement of tectonic stability (that means no subsidence in its plastic base or differential, vertical movement of its substratum of quartz phyllites). We use the altitude of 3100 m (in which a correction of 100 m for later erosive degradation is made) for comparison with the altitude of the pliocene surface (see also chapter VI, 2c). The rather widespread preservation of the oldest erosion surfaces shows the very slow rate of the post-oligocene erosion of such surfaces. This is explained by the fact that the truncated rocks are limestones and dolomites, which have no superficial drainage pattern but subterranean karst drainage. This tends to preserve (fossilize) the old surfaces, as has also been explained by Merla (1932, p. 48). The pliocene surface of the Alpe di Siusi and other areas in the neighbourhood of the Catinaccio group were only affected by postpliocene tectonic movements of minor importance, so that a mean altitude of 2100 m is reasonable. Thus the "normal" vertical separation might be estimated at about 1000 m.

This is confirmed by an estimate of the vertical difference of level of both surfaces in the Sasso Lungo group. If the vertical distance between the late pliocene level — which is at 2200 m at the base of the Sasso Lungo — were less than 1000 m, traces of an old erosion surface should be present in the Sasso Lungo summit which rises to 3181 m. As such erosion surface is absent, a minimal vertical separation of 1000 m can be accepted.

The vertical distance of about 1000 m is the initial (original) separation between the older and the younger level of erosion. However, disturbing vertical movements (especially subsidences) took place in many groups of the Dolomites between the Oligocene-Miocene and the upper Pliocene. The result is that the vertical separation between those subsided parts of the oligocene surface and the pliocene surface differs from place to place with the local geological circumstances. If our concept of the tectonic deformations in this area is correct, we come to the prognosis that the sum total of the estimated or measured vertical tectonic movement and the actually observed vertical separation must

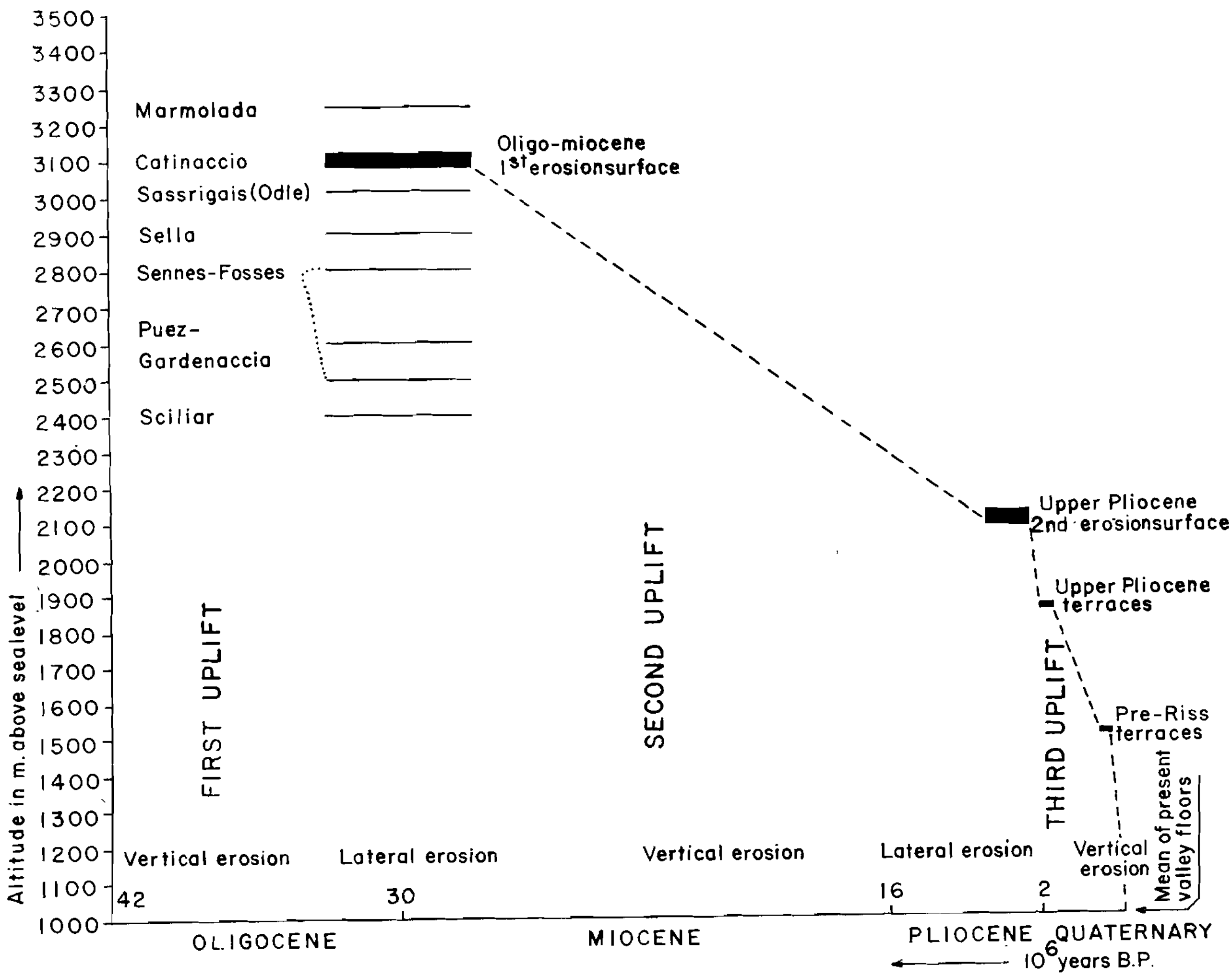



Fig. 17 The erosional history of the NW Dolomites in cenozoic time. The present mean altitude of the oligo-miocene erosion surface is indicated for the individual groups. The deviations from the "normal" altitude of 3100 m are caused by younger tectonic movements.

be in all cases about 1000 m. This appears to be really the case, so that the diagnostic facts support our working hypothesis.

The plateau of the Sciliar group has a mean altitude of 2400 m and must be considered as a part of the oligocene surface, which subsided together with the entire Sciliar reef mass along the Tires flexure-fault (see chapter VI, 2, c). The sum total of 1000 m is obtained when the throw of 700 m by the Tires fault is added to the vertical distance of 300 m occurring between the late pliocene level of the Alpe di Siusi and the Sciliar plateau.

The plateau of the Sella group has a mean altitude of 2900 m and a vertical distance to the late pliocene level of 800 m. When 200 m of the total, observed subsidence of 550 m are attributed to post-oligocene vertical movements (see chapter VII, 2) a total of 1000 m is found. This estimate of 200 m is reasonable because an important part of the subsidence must have preceded already the oligocene truncation. The Marmolada bulge — which was fed by matter squeezed out from the base of the Sella group — was already pushed up before the oldest erosion surface was formed. This greater age of the initial subsidence of this reef mass is proved by the existence of the summit thrusts upon the oligocene erosion surface of the Sella group. These summit thrusts are small nappes and/or "Klippen" which glided from the tilted and elevated northern limb of the Marmolada bulge over the depressed part of the oligo-miocene erosion level in the centre of the Sella reef.

A small relic of the oldest surface of erosion is found on the top of the Sass Rigais (3025 m) in the Puez-Gardenaccia-Odle group. There is a vertical separation of 925 m from the younger level of erosion, which occurs at the level of 2100 m. The Sass Rigais lies near the edge of the tilted basement block of Funes (see chapter VI, 2, a) and possibly a small uplift of some tens of meters should be subtracted. When we assume a subsidence in its plastic base within the order of magnitude of 100 m along the NW edge of the Puez-Gardenaccia-Odle group, roughly the sum total of 1000 m is found here too.

The base of the summit thrusts on the high plateaus of Puez and Gardenaccia — which is probably the original oligo-miocene surface — lies now at about 2600 m above sea-level. This implies a vertical distance of 500 m to the late pliocene surface in that area. A subsidence of 500 m of these reefs has to be assumed to come to a total of 1000 m. This is exactly the amount that it should be, according to estimates based on other grounds; the Puez-Gardenaccia group subsided almost as much as the Sella group, for which a subsidence of at least 550 m has been ascertained (see chapter VII, 2).

An erosian surface at the summit of the Marmolada group (Punta di Penia, 3344 m) was mentioned by Cornelius-Furlani (1927, p. 76). This is a relic of the oligo-miocene surface. It was tilted in later time and is found now at the mean altitude of 3250 m. This implies a vertical distance to the late-pliocene level (for instance in the Fedaja Valley) of 1150 m. This increase of 150 m over the original vertical distance of 1000 m is due to tectonic arching up. The tilt and the slight uplift of the older surface of erosion took place when the Marmolade bulge evolved into a pierced diapir in the Miocene and lower Pliocene (see chapter VII, 7).

Remnants of a high (older) erosion surface were observed by Merla (1932) in the Sennes group along the northern border of the Dolomites. Their present altitude is 2500-2800 m (see chapter VI, 3). The vertical separation of 400-700 m from the younger erosion surface requires vertical tectonic subsidence of 600-300 m in that area. Such subsidence must be assumed for that group from a tectonic standpoint as well, because this subsided zone forms a synclinal depression southwest of the anticlinal basement structure of Vallandro (see chapter V, 3 and VI, 3).

The following arguments for a late oligocene to early miocene age of the oldest erosion surfaces in the NW Dolomites can be advanced:

1) The oldest level could be dated by means of correlate sedimentation in the Venetian foreland as oligo-miocene (Nangeroni, 1938; Rossi 1957).

2) The relics are found above the widespread "Tre Passi" level, for which generally a late pliocene age is accepted (Rossi, 1957; Winkler von Hermaden, 1957). The surface must consequently be older.

3) The Tires fault is synchronous with the faulting and intrusion of tonalites along the Judicaria-Pusteria fault. The oligo-miocene age of these intrusions (see for instance Van Hilten, 1960, p. 32) gives us also the age of the Tires fault. Since the erosion surface of the Sciliar plateau would come nearly at the altitude of the summit level of the western Catinaccio group if the necessary correction of 700 m for the movement along the Tires fault is made, we may assume the following:

The Sciliar plateau is the undissected, though subsided remnant of an erosion surface of at least oligo-miocene age, which can be connected with the summit level of the western Catinaccio group, which is the dissected and somewhat lowered initial surface.

The oligo-miocene erosion surface was dissected during the Miocene and lower Pliocene (see for instance Nangeroni, 1938, p. 20). Nangeroni found in the Sella group relics of minor erosion surfaces at 2600 m (the Raibl terrace) and at 2350 m (the system of terraces of M. Forca). The uppermost tracts of some tributary valleys of the Avisio in the Catinaccio group may belong to the fluvial system which corresponded with the Raibl terrace (see chapter VI, 2, c).

The upper pliocene erosion surface has a wider distribution than the oligo-miocene one. It is present in the entire southeastern Alps. This surface was described by Von Klebelsberg (1935, pp. 422-441) as "middle tertiary alpine surface" ("die mitteltertiaire Gebirgsoberfläche"), and its age was originally considered to be miocene. However, investigations by Merla (1932), Nangeroni (1938), Rossi (1957) and Winkler von Hermaden (1957) — which were partly based on the study or correlate sediments in the venetian foreland by Venzo (1934), Cita (1955), Accordi (1955, b) and others — all point to an upper pliocene age. The altitude of this surface in the NW Dolomites ranges from 1900 m to 2300 m, with a mean of about 2100 m (Nangeroni, 1938, p. 20; Von Klebelsberg, 1938, p. 436).

This erosion level cuts across all stratigraphic levels of the Permo-Triassic and it is also present in the area of quartz phyllites (the Pusteria Valley north of the Dolomites).

Almost all important passes (the Passo di Gardena, the Passo di Pordoi, the Passo di Sella, the Passo di Falzarego, the Passo di Valparola, the Passo di Giau etc.) and high terraces with alpine meadows (the Buffaure area, the Campolongo area, the Alpe di Siusi, the Alpe di Sennes, the Alpe di Faloria, the Alpe Vallandro etc.) belong to this surface. The upper courses of many valleys represent in most cases the pliocene valley tracts which are only slightly lowered (the Valley of Contrin, the Fedaja Valley, the Valley of San Nicolò, the Monzoni Valley, the Fanes Valley, the Travenanzes Valley etc.).

The reader is referred to Von Klebelsberg (1935, pp. 433-438) for more factual information.

The late pliocene erosion surface was warped down at some places by the lateral flow of underlying matter to the horizontal diapirs in the sides of the younger rejuvenated valleys (see fig. 47 and chapter VII, 4).

The pliocene erosion surface has been dissected since the upper Pliocene by fluvial and glacial erosion. At least two minor interruptions of this vertical erosion with its corresponding terraces can be distinguished.

A valley system of the uppermost Pliocene is partly preserved at 200-400 m below the pliocene surface at 1800-1850 m above sea-level. To this system belong the broad valley across the Campolongo pass, parts of the Avisio Valley and of the valleys of San Nicolò, of Monzoni, of Pellegrino, of Antermoia etc. Terraces of this valley system are found in the Cordevole Valley (see van Klebelsberg, 1935, pp. 454-455). The oldest series of the sideward diapirs to the floors of the valleys corresponds with this terrace- and valley floor system (see chapter VII, 4 and VII, 5).

A younger terrace system at 1500-1550 m above sea-level occurs in the Cordevole Valley, the Avisio Valley (Val di Fassa), near Podestagno (Peitlstein, see Von Klebelsberg, 1935, pp. 455, 465), in the Pusteria Valley etc. This level was the base level for a second (lower) set of sideward diapirs to the floor of the Cordevole Valley.

Von Klebelsberg attributes a pleistocene, pre-Riss age to it. Small relics of a badly developed system of younger pleistocene and holocene valley bottoms occurs, but so far little morphologic study has been dedicated to this youngest system. The present valley bottom of the Fassa Valley serves also as a temporary base level for the sideward squeezing out of matter, the "horizontal diapirism" in this area.

# CHAPTER V

# THE TECTONICS OF THE BORDER ZONE OF THE DOLOMITES

The rise of the alpine geanticline in the early Tertiary caused gravitative reactions in its tilted sedimentary cover (fig. 1 and 18). West of the Dolomites — in the Val-di-Non area — Van Hilten (1960) found WSW-ENE fold axes and a SSE-ward sliding movement of a sedimentary slab, the Taio upthrust of the Val-di-Non — Mendola unit. South of the Dolomites, in the Lessinian area of the Southern Limestone Alps E-W striking and southward overturned folds, described by Pia (1923), were interpreted by De Boer (1963, p. 129) as the effect of the southward décollement of the sedimentary cover from the rising alpine geanticline. Moreover, Van Hilten proved that the NE-SW trending Judicaria fault was formed after the phase of décollement of the epiderm by means of the upward drag of the pre-existing fold axes. In other words this fault is somewhat younger than the initial stages of the rise of the east alpine geanticline (Van Hilten, 1960, fig. 38 on p. 66 and fig. 39 on p. 70). The Judicaria fault reached a vertical throw of 5-9 km and, locally, rifts with narrow sunken wedges of sediments (due to the formation of Y-faults) developed along its SE side.

The décollement and the erosion caused the removal of the sedimentary epiderm from the central parts of the east alpine geanticline north of the Judicaria-Pusteria fault system. Only some isolated wedges of sunken units of the permo-mesozoic cover do occur in rifts, representing relics of this cover north and northwest of this fault line (Innervillgraten, Mauls, Col d'Isarco and Schneeberg). These wedges are the effect of tensional phenomena in the crystalline basement. Similar tension phenomena occurred along the main fault system itself during its initial stages of development (Van Hilten, 1960; Agterberg, 1961, fig. 74 on p. 84). Moreover, the wide belt of mesozoic (and eocene) strata between the Judicaria fault and the Adige Valley may be considered as a belt of relative subsidence between the central Alps and the central Dolomites (see following part V, 1 and V, 3).

The further rise of the east alpine geanticline resulted in a bending over of the upper parts of the normal faults towards the downthrown side by gravitative spreading of the elevated blocks (see Van Bemmelen, 1960 a and b, and chapter I, 8). Thus the present outcrops of these faults have the character of apparent, steep upthrusts.

This concept was proved to be correct by means of elaborate, statistically analyzed data on minor tectonic elements (Dietzel, 1960; Van Hilten, 1960; Agterberg, 1961).

## V, 1. BROAD STRUCTURAL OUTLINE OF THE WESTERN BORDER.

SE of the Judicaria fault follow some horstlike uplifts inside the belt of subsidence (the Ivigna and M. Croce horsts, with a maximal width of 6-7 km). These uplifts are caused by the upward push of tonalitic magma, which ascended diapirically in this belt of pressure relief (fig. 9). The intrusions can be considered to be apophyses (offshoots) of the main body of granitic magma which formed the palingenetic magmatic root (asthenolith) underneath the adjacent alpine geanticline. These horsts are bordered to the SE by the Nova and Foiana faults (Dietzel, 1960, fig. 28, p. 41; Van Hilten, 1960, fig. 39c, p. 70).

SE of these tonalite-diapirs follows a belt of subsidence, the Brenta- Val di Non- Mendola area, about 20 km wide. A drilling by the AGIP in the Val di Non in 1958 reached the top of the Bolzano quartz porphyries at 1620 m below sea level. The contents of this subsided zone was slightly compressed and imbricated by compressive settling. A much more pronounced case of compressive settling is found in the Lienz Dolomites and Gail Alps (Drava or Drau rift zone), farther east along the periadriatic suture (Van Bemmelen, 1957, 1961).

The Brenta - Val di Non - Mendola belt is bordered to the SE and E by the Adige Valley, east of which the Bolzano quartz porphyries reach altitudes of 2500 m.

### The southern Adige fault

The Adige Valley probably coincides with a system of faults extending between the belt of subsidence west of it and the high plateau of quartz porphyries to the east. The inferred fault system through the Adige Valley between Lavis and Bolzano might be called the southern Adige fault. The following arguments are considered as indications for it:

1. The difference in altitude of the top of the quartz porphyries in the Val di Non and those east of the river is at least 3000 m.
2. This part of the Adige Valley concurs with the hinge line between the subsided Val di Non area and the plate of quartz porphyries of Bolzano.
3. The series of cross sections over the Adige Valley by Von Klebelsberg (1935, Beilage 9) shows obvious differences in dip on either side of the valley.

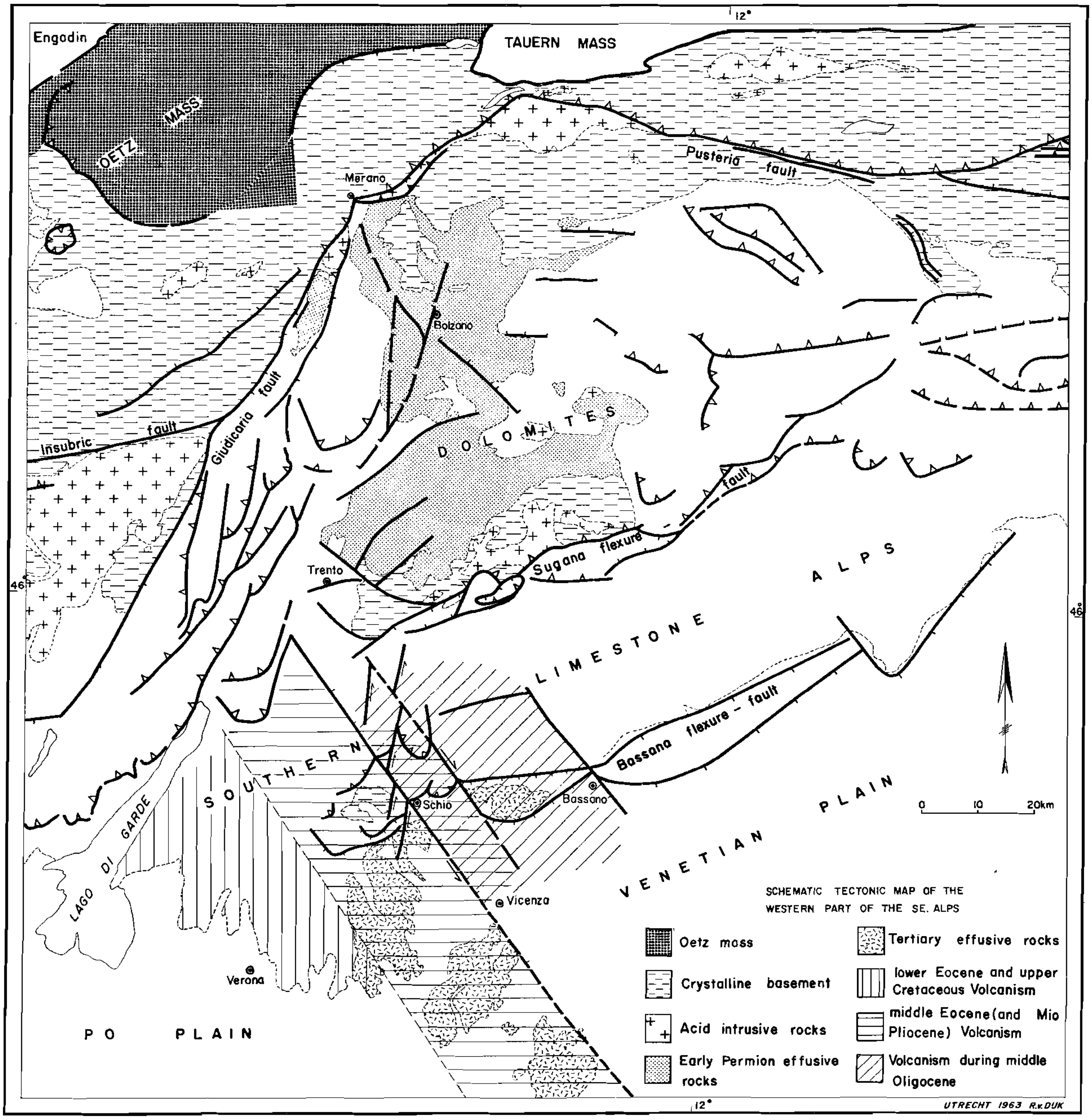



Fig. 18 Geological sketch map of the NW Dolomites and their border zone after De Boer (1963), slightly modified.

4. This tract of the Adige Valley is rectilinear and crosses the stratigraphic boundaries obliquely, which indicates structural control of its course.
5. This southern part of the Adige Valley is parallel to the Judicaria fault. The fault coinciding with this valley would be a westward dipping normal fault, bounding the Brenta-Val di Non - Mendola belt of subsidence to the east.
6. A direct continuation of this fault might be found in the Sarentino Valley where he inferred Sarentino fault (see chapter V, 2) forms its northward extension.

The northwestern Adige fault

The subsided zone of Brenta-Val di Non-Mendola is bordered to the north by the Adige Valley between Bolzano and Merano. The fault or flexure, coinciding with this part of the river course will be called the northwestern Adige fault. The following arguments for its existance can be given:
1. The subsided Val-di-Non area must be connected with the structurally about 3000 m higher, flat-lying plate of quartz porphyries northeast of the Adige Valley by a flexure or fault.
2. The straight course of the Adige Valley indicates structural control.
3. The absence of shear joints in the quartz porphyries along the valley suggests tension.

These three points were given by Van Hilten (1960, p. 64) who assumed a hinge line here and along our southern Adige fault.

The Caldaro fault

The northwestern Adige fault (see fig. 18 and 19) joins a smaller secondary fault near S. Paolo (west of Bolzano) and there the Adige Valley suddenly widens. This fault — the Caldaro fault — extends from S. Paolo along Caldaro to Egna (Neumarkt). Between this eastward dipping Caldaro fault and the west dipping southern Adige fault the elongate, triangular block of quartz porphyries of Caldaro is intercalated. This Caldaro block tilted and subsided between both faults.

This situation explains several morphological features in this part of the Adige Valley. The subsidence of the block makes the abrupt widening of the Adige Valley near Bolzano comprehensible ("Bozener Talweitung"). The occurrence of an old, now abandoned course of the Adige to the west of its present river bed appears to be related to this faulting. This former course of the Adige coincides with the western edge of the tilted and subsided block of Caldaro.

## V, 2. BROAD STRUCTURAL OUTLINE OF THE NORTHWESTERN BORDER.

Epi and mesometamorphic quartz phyllites and a part of the plate of quartz porphyries of Bolzano crop out in the area extending between the Judicaria and Pusteria faults in the NW and N, the northwestern rim of the Dolomites in the SE, and the Val-di-Non area in the SW (see fig. 18). The area is subdivided into some morphologic units by the valleys of the Adige, the Sarentino, the Isarco, the Tires and the Funes. Almost all major valleys coincide with normal faults. The fault system in this area developed in combination with the formation of the great, normal peri-adriatic Judicaria and Pusteria faults with their vertical throw of 5 and more kilometers. Some of these secondary faults in the marginal belt of the downthrown Dolomites area such as the Funes-, Tires-, and Trodena fault lines have already been described in the literature; but some others are less conspicuous. Their presence can be surmised only by means of circumstancial evidence, e.g. the southern part of the Sarentino fault, the Isarco fault and the Passirio fault. Some arguments for their existence will be given here (see fig. 18):

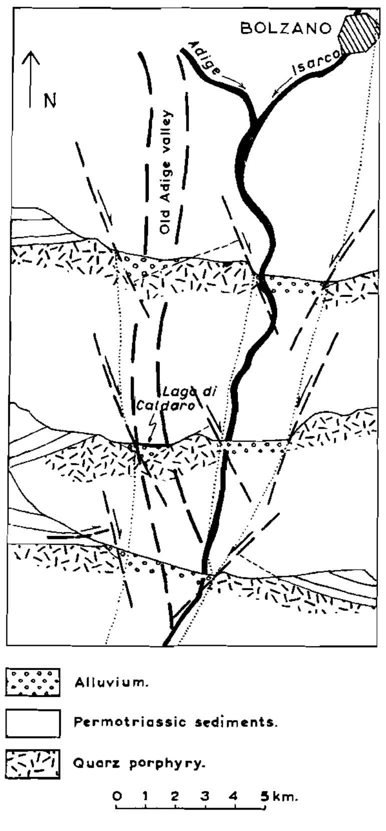



Fig. 19 Subsidence and tilt of the Caldaro block between the westward dipping southern Adige fault and the antithetic, eastward dipping Caldaro fault, modified after Von Klebelsberg (1935, Beilage 9).

### The Sarentino fault

Dietzel (1960, p. 35-36, fig. 2) found a NW-SE striking normal fault, dipping 40° SW along the northeastern margin of the quartz porphyries to the west of the Sarentino Valley. The vertical throw is at least 150 m. This fault can be followed still farther in NNE-SSW direction along the lower course of the Sarentino Valley to Bolzano. It might be called the Sarentino fault over its full length from the Mt. Ivigna to Bolzano. Arguments for this extension of the already known part of the fault are:

1) The fault observed by Dietzel does not end abruptly but should mechanically have a logical continuation.
2) The long straight lower course of the Sarentino points to fault-control.
3) The plate of quartz porphyries between the SW part of the Nova fault, the Adige fault between Merano and Bolzano, and the Sarentino fault forms a separate, flat-lying unit with a regular outcrop pattern of post-permian alpine formations, which are nearly lacking on the block to the east of the lower Sarentino Valley.
4) The connection of the Sarentino fault with the Adige fault south of Bolzano gives a good structural closure along the northern side of the great NNE-SSW trending, subsided zone along the Judicaria fault (Val-di-Non and Brenta areas).

### The Isarco fault

Another important fault in the blockfaulted area follows the lower Rienza from Vills to Bressanone, and the Isarco from Bressanone to the mouth of the valley of Tires. It will be called the Isarco fault.

Some arguments for its existence are:

1) The Isarco Valley is remarkably straight over a long distance and crosses structural lines and stratigraphic boundaries obliquely.
2) At Ponte Gardena (Waidbruck) the eastern side of the valley is built up by quartz porphyries, the western side on the same altitude by the older quartz phyllites.
3) Neither the Funes fault (see following paragraph) nor the normal fault in the valley of Castelrotto with its throw of 300 m (Fior, 1957) have a definite continuation west of the Isarco Valley.
4) Steep to vertical dips to the NNW occur in the quartz porphyries near the mouth of the Tires Valley, almost parallel to the southernmost NE-SW part of the Isarco fault.
5) Already Mojsisovics (1879, p. 127-128) attributed a graben-like origin to parts of the Isarco Valley.
6) The contact plane between porphyries and Gardena sandstones is found at 1000 m near the Sciliar group, but Gardena sandstones are found not even at 1252 m on the Ritten to the west of the Isarco (Mojsisovics, 1879, p. 127-128). It implies a minimum downthrow at the side of the Dolomites of 250 m.
7) When approaching the Isarco Valley in the area of Bressanone, the iso-lines of mean azimuth of minor folds in the quartz phyllites (Agterberg, 1961, sheet IV) show deviations and bends.
8) The outcrops of the stratigraphic levels in the phyllites and the porphyries strike NW-SE to the west of the Isarco Valley and cannot be followed without breaks into the ENE-WSW striking limits of the outcrops east of the river.

From the distribution of the stratigraphic units on the opposite sides of the Isarco Valley it may be concluded that the whole block east of the river rotated around a west-east axis south of Chiusa (Klausen) and has got a dip to the south of some degrees. The smaller west-east faults of Funes and Tires within this major block are described in the following paragraphs.

### The Funes fault

This is a normal fault in the basement which strikes from the Isarco Valley in eastern direction through the Funes Valley into the NW Dolomites.

The northern block subsided. The throw decreases from a maximum in the west to zero in the anticline of Passo Poma, north of the Puez-Gardenaccia-Odle group. There the fault fades out under the thick cover of epidermal alpine sediments. It can be considered as an antithetic fault conjugate with the huge normal Pusteria fault. The basement block of quartz phyllites, limited by the Funes fault and the northern part of the Isarco fault tilted to the south because of the antithetical rotation and has at present a mean dip of 40° SSW (Agterberg, 1961, sheet IV).

This dip is probably also partly due to updoming by the intruding mass of the Bressanone granite. Local complications and details of this fault will be treated in chapter VI, 2, a.

### The Tires fault

The Tires fault has the same character as the Funes fault north of it. Here too, the northern block subsided. The Isarco follows the fault from the valley of Tires to Bolzano. The eastern continuation of the fault is observed in the Tires Valley where the fault changes into a flexure and disappears still farther east in the Catinaccio group. The basement north of what has been called the "line of Tires" in the literature, has a slight southward dip (estimated at 5°-7°) by rotation of the block to the north. The details of this fault will be described in chapter VI, 2, c.

### The Passirio fault

Another fault, somewhat different by its position in the elevated block along the Judicaria and Pusteria faults, lies northwest of Merano.

The Passirio Valley (Passeier Tal) from St. Leonhard to Merano follows this fault.

The following points are considered as evidence:
1) The Passirio Valley has a very straight course over a long distance and crosses the stratigraphic boundaries obliquely. This suggests structural control.
2) The Passirio Valley forms the immediate continuation of the Foiana fault south of Merano.
3) Seismically the Passirio Valley is known as an active line (Von Klebelsberg, 1935, p. 382).
4) The strike lines of the gneisses show slight deflections from their direction near the Passirio Valley (see Agterberg, 1961, sheet I).
5) When important faults change their direction, they often have minor faults which splay off and fade out. The Judicaria fault changes its direction at Merano, changing from N 35° E to N 55° E; the Passirio fault might be considered as such a splay-fault forming the extension of the Judicaria fault, fading out NNE-ward.

The area fringing the northwestern Dolomites can thus be explained as a block-faulted border zone along the peri-adriatic suture. This zone separates the uplifted geanticlinal core of the central eastern Alps from the less elevated Dolomites. The vertical throw along the normal Judicaria and Pusteria faults is about 5-9 km (Dietzel, 1960, van Hilten, 1960 and Agterberg, 1961). The time of origin of the faults in this fractured border zone will be fairly synchronous with the age of the Judicaria and Pusteria fault systems, being a tension zone of tilting and subsiding blocks parallel to them. Dietzel (1960, p. 27) gives a mid-tertiary, pre-miocene age for the intrusion of the peri-adriatic tonalites. Van Hilten (1960, p. 66) gives a late-oligocene age for the Judicaria fault. This is in good accordance with the late-oligocene age of the Tires fault, which was dated by means of relics of erosion levels (see VI, 2, c).

The discussed block-faulted belt forms the northeastward extension of the Val-di-Non and Brenta areas, which represent also subsidence blocks along the Judicaria fault farther south.

## V, 3. BROAD STRUCTURAL OUTLINE OF THE NORTHERN AND NORTHEASTERN BORDER.

The tectonics of the Pusteria fault and of the quartz phyllites of the Pusteria Valley along the northern border of the Dolomites were recently studied by Agterberg (1961) by means of a statistical analysis of micro-tectonic data.

He concluded that the Pusteria fault was originally a southward dipping normal fault with a throw of some kilometers, in accordance with Van Bemmelen's concept of the east alpine mountain building (1960 a). The Pusteria fault belongs to the Insubric-Judicaria-Pusteria-Drau fault system, which developed during the Oligocene-Miocene in the southern limb of the alpine geanticline. In some places the fault was bent over into a northward dipping position under the influence of a gravitational spreading of the higher parts of that geanticline. A small tension rift parallels the fault at its southern side (see Agterberg, 1961, fig. 68 and 74), and it was filled with blocks of mesozoic sediments. Tonalitic magma intruded along the fault system. Next thereupon the section of the Pusteria fault between Brunico and Sillian rotated into a 50°-70° N dipping position owing to the gravitational stress field created by the geanticlinal culmination of the Tauern.

The zone of pre-permian quartz phyllites between the Pusteria fault and the permo-triassic strata of the Dolomites has a schistosity which is generally parallel to the sedimentary bedding. The quartz phyllites dip 15° - 50° to the S or SSW at the west side of the Pusteria Valley in the Bressanone area (see Agterberg, 1961, sheet IV). Farther east, in the surroundings of Brunico, the schistosity becomes subvertical and the rocks are probably compressed in isoclinal major folds with an E-W axis (see Agterberg, 1961, fig. 59). This is confirmed by the occurrence of a syncline of well-bedded limestones in the quartz phyllites near Brunico (Agterberg, p. 74).

The width of the zone of quartz phyllites decreases from 7 km near Sorafurcia in the west (east of Brunico) to 2 km at San Candido in the east.

Agterberg made probable to accept a clockwise rotation of the Pusteria fault plane along a subvertical hinge line NW of Brunico. Because of this rotation the belt of outcropping quartz phyllites was narrowed from 7 km at the hinge line to 2 km about 20 km farther east. By this rotation the quartz phyllites were squeezed diapirically upward in the Eggerberg structure, near Monguelfo (see Agterberg, 1961, fig. 64).

Agterberg initially assumed that the Eggerberg structure had an anticlinal form, due to this diapirical upward movement. By studying the rotation of the minor fold axes in the quartz phyllites he concluded to upward vertical movements of diapiric character in this local structure of at least 6 km. However, it seems also possible that the Eggerberg structure was originally a (southward overturned) syncline. The contents of this syncline were then squeezed upward diapirically in an echelon pattern of smaller structural culminations and depressions (see Agterberg, 1961, sheet III a and chapter 12). In this way the variations in dip of the axes of the minor folds are explained too, and it is no longer necessary to accept locally restricted vertical movements of such great amplitude (6 km or more) within the Eggerberg structure. The pattern of mean azimuth lines (which are also approximately the mean strike lines of the vertical schistosity and the strike lines of the bedding planes) can thus be interpreted as a simple synclinal strike pattern. Agterberg agrees with this new interpretation (personal communication). The syncline is made visible

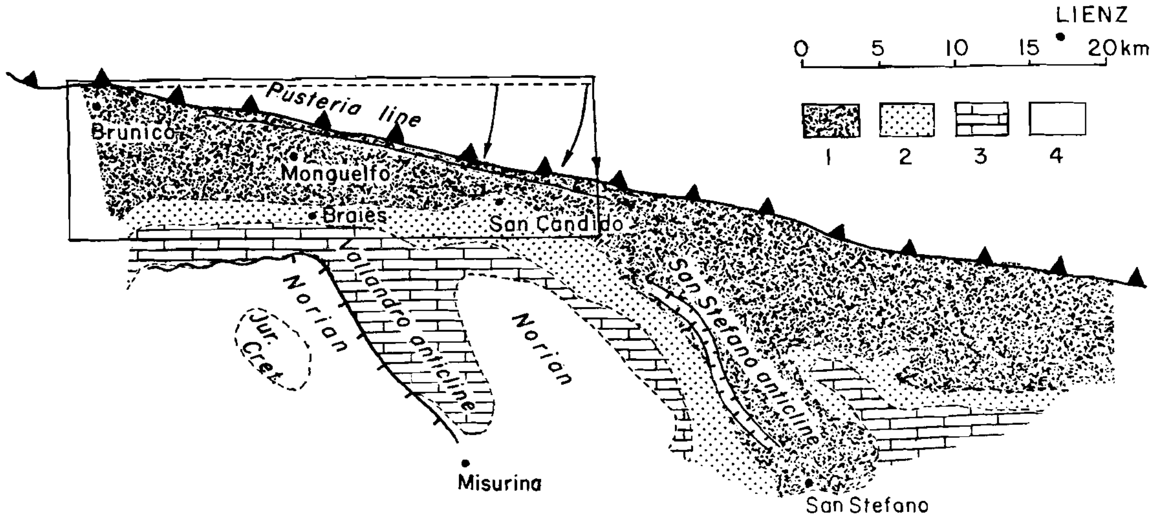



Fig. 20 Geological sketch map of the Pusteria region and the northern border of the Dolomites. The NW-SE trending anticlinal structures in the basement at San Stefano and Vallandro (caused by the dextral rotation of the Pusteria fault) are visible in the outcrop pattern of the NE border of the Dolomites 1. quartz phyllites of the Pusteria Valley 2. Permian and Lower Triassic 3. ladino-carnian dolomite 4. norian Hauptdolomit and younger rocks.

by green phyllites near Monguelfo (Agterberg, p. 31), which fits well in with this picture, as it lies in the centre of the synclinal strike pattern.

The above re-interpretation of Agterberg's data can be summarized as follows:
A zone of subsidence fringes the Judicaria-Pusteria fault system from Lago di Garda via the Brenta Alps, and Val di Non to the Pusteria zone, from Bressanone across Brunico to San Stefano di Cadore (see also chapter V, 1 and V, 2). A gradual transition occurs between the subsided zone parallel to the Judicaria fault (Brenta and Val di Non) over the southward dipping quartz phyllites of Bressanone to a synclinorium in the quartz phyllites near Brunico. The latter extends eastward in the synclinorium between Brunico and Prato alla Drava, which was transformed into a kind of "sag-syncline" ("Beutelsyncline") due to the toppling over and the dextral rotation of the Pusteria fault. The contents of this syncline were diapirically squeezed upward.

The eastern part of the Pusteria Valley between Braies and San Stefano is situated between the subsided centre of the Dolomites to the SW and the uplifted Tauern centre to the NE. This uplift initiated a southwestward compressive stress of gravitative character in the southwestern limb of the alpine geanticline. The dextral rotation of the Pusteria fault plane to the SW, found by Agterberg, can be explained in this way. The upward squeezing of the quartz phyllites by this rotation of the Pusteria fault during the Miocene (this age will be discussed in chapter VI, 3) was mainly restricted to the erosional carve of the Pusteria Valley, where an outlet for upward diapirism was afforded.

Although less intense there, the influence of this SW-ward push can still be found in the basement below the heavy and rigid cover of dolomite along the northeastern border of the Dolomites. Two large anticlinal NW-SE trending structures occur in this marginal zone. They fade out to the SE under the epidermal cover of the central parts of the Dolomites and merge at their NW side with the diapiric Eggerberg structure of the Pusteria Valley (fig. 20). The northward indentures in the strikelines of the Eggerberg "sag-syncline", SW of Monguelfo and W of San Candido (see fig. 21), are probably genetically related with the branching off of these major warpings in the NE Dolomites.

The first of these anticlinal basement structures extends from San Stefano di Cadore to San Candido. Agterberg, who studied this region, found a SW-ward overturned anticlinal structure of quartz phyllites with a vertical amplitude of about 2,8 km (Agterberg, 1961, p. 66). The crest of this anticline in the quartz phyllites contains wedges of Gardena sandstones which strike roughly parallel to the schistosity planes of the phyllites.
Cornelius-Furlani (1902) gave two alternative explanations for the occurrence of these wedges of younger rocks:
a) the overlying sedimentary rocks were folded

and the synclines were pressed downward into the basement,

b) the overlying sedimentary cover subsided as wedges into tension rifts of the basement.

Agterberg proves that the first explanation cannot account for all field observations and he favours the second hypothesis. This tension hypothesis requires the assumption of a phase of tension in the subvertical phyllites with the formation of graben structures. This phase of rifting was then succeeded by compression and rotation. A similar sequence of events has been observed along the Pusteria fault and the Gail rift.

The second NW-SE extending anticlinal basement structure in the northern margin of the Dolomites does not expose outcrops of quartz phyllites, but it can be recognized in the outcrop pattern of the norian Hauptdolomit and the ladino-carnian dolomite between Braies, Cortina d'Ampezzo and Auronzo. This structure will be called the Vallandro anticline. The eastern one of the two anticlinal basement structures — the San Stefano anticline — is bordered to the southwest between Auronzo and the mouth of the Rienza Valley by a zone of flatlying Hauptdolomit forming the summits. No relics of Hauptdolomit occur, however, in a 7 km wide NW-SE striking zone along the Rienza Valley. This uplifted anticlinal zone is separated from a SW-ward imbricated, subsided zone to the SW by a flexure-fault. This flexure-fault extends from the neighbourhood of Braies to Misurina; it is discussed more in detail in chapter VI, 3. The higher Vallandro zone, where Hauptdolomit is lacking, lies exactly in the extension of the deviating bend in the strike lines of the Eggerberg structure SW of Monguelfo.

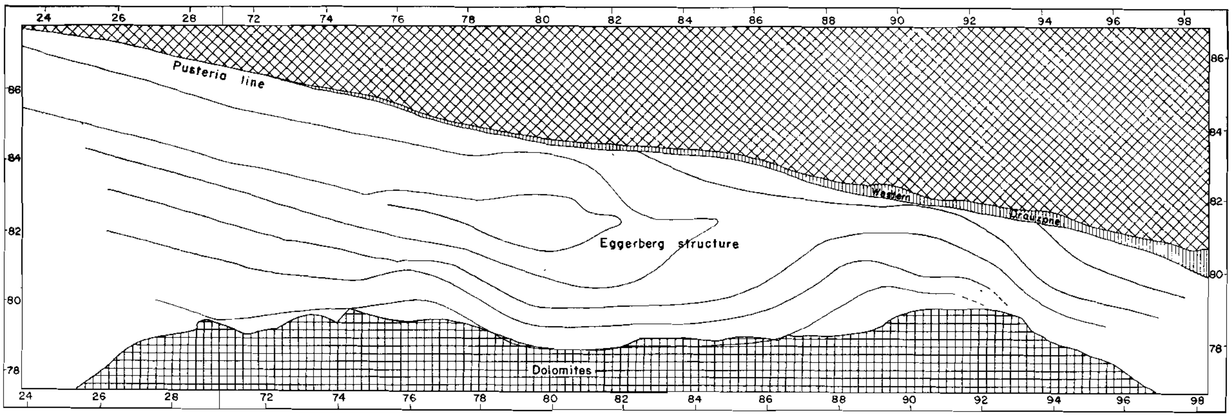



Fig. 21 Structure map of the quartz phyllites to the south of the Pusteria line between Brunico and Prato alla Drava. The lines in the quartz phyllitic area represent the mean azimuth lines of the minor folds ≈ the mean strike lines of the subvertical schistosity ≈ the mean strike lines of the bedding planes, after Agterberg (1961, sheet III, a) modified. See for further explanation the text.

## V, 4. BROAD STRUCTURAL OUTLINE OF THE SOUTHERN BORDER.

Whereas phenomena of rifting and normal faulting can be observed in the basement complex along the northern (Pusteria) and western (Judicaria) side of the Dolomites, the WSW-ENE belt of basement rocks between Trento and Agordo represents a major pressure belt with considerable uplifts at the southern side. Around Levico, in the Cima d'Asta area and in the Gosaldo anticline the crystalline basement complex is exposed and reaches considerable altitudes (Cima d'Asta with 2848 m). The southern side of this pressure belt is bounded by the great Sugana fault and fault graben, which is cut off at its western end by the NW-SE trending normal faults between Lavis and Levico (see, for instance, De Boer, 1963, fig. 39).

We suggest that this southern margin of the Dolomites can be considered as a pressure belt in the basement complex, formed in the lower part of the flank of the elevated east alpine geanticline with NE-SW trending structures in it: the Trodena horst (Venzo, 1962), the Lagorai-Cima d'Asta range, and the Gosaldo anticline.

The Cima d'Asta and Gosaldo structures (Agterberg, 1961, 1963 in press; d'Amico, 1963, in press) seem to be cut off by the younger Sugana flexure-fault and graben. The presence of such a pressure belt due to stress gradients radiating from the elevated hinterland (with higher potential energy) to the subsided foreland (with lower potential energy) was described for a comparable situation in the Naukluft Mountains (SW Africa) by Korn and Martin (1959), see also chapter I, 8 and fig. 6, b.

## V, 5. CONCLUSIONS ON THE TECTONICS OF THE BORDER ZONE OF THE DOLOMITES.

Summing up, we may say that the Dolomites appear to be framed by a belt of tensional movements at the W, NW, N and NE side, (from Lago di Garda by way of Brenta-Val di Non - Mendola - Sarentino - Pusteria - to S. Stefano di Cadore) and a pressure belt at their S(E) side (see fig. 1, 2, 18). The tension phenomena as well as the pressure phenomena decrease in magnitude from west to east. At the easternmost end San Stefano di Cadore seems to be a hinge point for a slight anticlockwise rotation of some degrees of the Dolomites-block as a whole in cenozoic time. The tensional features along its northern margin and the pressure phenomena at its southern border can be considered as the mutually compensatory mechanical effects of this rotation.

This rotation, however, is another, much younger and smaller one than the older rotational movements which De Boer (1963) assumes on paleomagnetic evidence.

# CHAPTER VI

# THE GRAVITY TECTONICS IN THE SEDIMENTARY EPIDERM OF THE NW DOLOMITES, RESULTING FROM THE TECTONIC DEFORMATIONS OF THE BASEMENT

## VI, 1. EPIDERMAL GRAVITY TECTONICS OF THE WESTERN AND SOUTHERN BORDER OF THE DOLOMITES.

In chapter V, 1 we mentioned already the folding and thrusting movements with gravitative character which are restricted to the sedimentary cover. This décollement resulted from the general tilt in the flank of the geanticline.

Moreover, secondary reactions to the differential, vertical movements of the basement occurred. Agterberg (1961) described the formation of Klippen which slid into the Val Sugana graben and the décollement of the Tudaio block near San Stefano di Cadore. The tectonics of the epiderm along the Trodena line (Venzo, 1962) can probably be considered as the draping of the sediments over a squeezed-up wedge of the underlying basement. In the Vicentinian Alps (south of the Dolomites) De Boer (1963) found also many local gravitative reactions of the sedimentary cover to the tectonics of the basement. There are many examples of gravity tectonics in the epiderm in the Merano and Val-di-Non areas (Dietzel, 1960; Van Hilten, 1960) induced by the tectonics of the basement. Examples in the Brenta Alps can be derived from the maps and sections of Wiebols (1938) and Trevisan (1939, a and b).

## VI, 2, a. THE FUNES FAULT.

The Funes Fault (Vilnösser Linie) is a zone of dislocation, extending along the valley of Funes from its mouth in the Isarco Valley in the west to the valley of Longiaru (Campil) in the east. Near Spessa (Spiess) the permian and triassic rocks of the northern block abut against the pre-permian quartz phyllites to the south, which form the ridge between the valleys of Funes and Gardena. The throw of about 1000 m near Spessa diminishes eastward to zero in the anticline of Passo Poma west of Longiaru.

Opinions on the regional tectonic importance of this fault differ widely. Mojsisovics (1879, p. 221) considered it as a vertical, normal fault with a downthrow of the northern block. Cornelius-Furlani (1924, p. 127) thought that the dislocation was a steep, northward upthrust with strongly varying horizontal displacement, reaching a maximum of 300 m near Spessa. Mutschlechner (1933 a, p. 99) believed that the sedimentary thrust masses had dragged slices of the crystalline basement (quartz phyllites); he assumed spoon-shaped thrust planes through the gypsiferous marls of the lower-Bellerophon deposits. Regionally Mutschlechner did not attach a great importance to this fault as it cannot be traced very far neither to the Badia area, east of the upper course of the Funes valley nor to west of the Isarco Valley. Von Klebelsberg (1935, p. 375) subscribed to Mutschlechner's idea of an imbricated, northward structure. Neither did Heissel and Ladurner (1936, p. 29) find a clear westward continuation of the line near the Isarco.

Finally, Leonardi (1955 a, p. 57 and Tav. 38) believes the Funes line to be a part of the anticline of Passo Poma; the Funes dislocation is one of the major, regional lines in Leonardi's tectonic scheme of the Dolomites and is considered as the upthrust southern limb of the anticline of Passa Poma ("piega-faglia"). Leonardi is of the opinion that this dislocation is of a great regionality for, according to his concept, it should be traceable from the Isarco Valley in the west as far as Cortina d'Ampezzo at the eastern side of the Dolomites.

According to the present author the Funes line developed as a normal fault, limiting a basement block of quartz phyllites. This block tilted slightly to the south by a rotational movement. This rotation might result from antithetic movements along the great normal Pusteria fault, north of it. The basement block under discussion is limited to the west by the SW-NE extending Isarco fault. The Funes fault fades out to the east beneath the sedimentary cover of Permo-Triassic in the area of Longiaru-Badia. The length of this fault is about 20 km.

The tectonic structure of the basement of quartz phyllites and the overlying epiderm of Permo-Triassic will be discussed according to Sanford (1959). This author experimented with a model where a step in vertical displacement was applied to the lower boundary of a homogeneous plastic layer with cohesive strength (fig. 7a). The characteristic fracture pattern that developed during this experiment was a series of curved reverse faults above the downthrown block, and a series of normal faults in the elevated block. The reverse faults start as vertical normal faults at the lower boundary of the epiderm but become apparently steep upthrusts in its upper part. The low angle of the fault near the upper surface is due to horizontal compressive stresses which developed at that place. However,

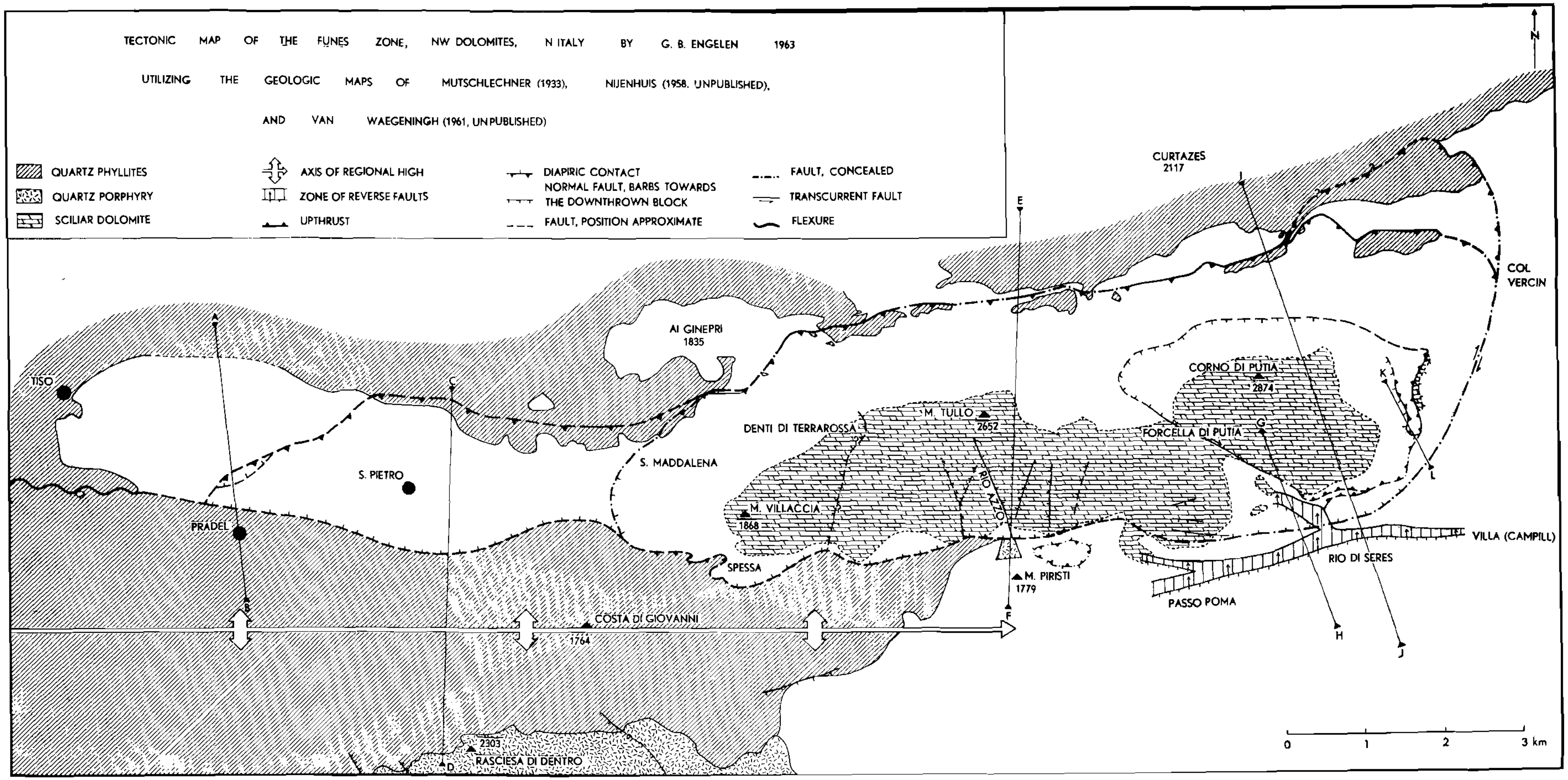
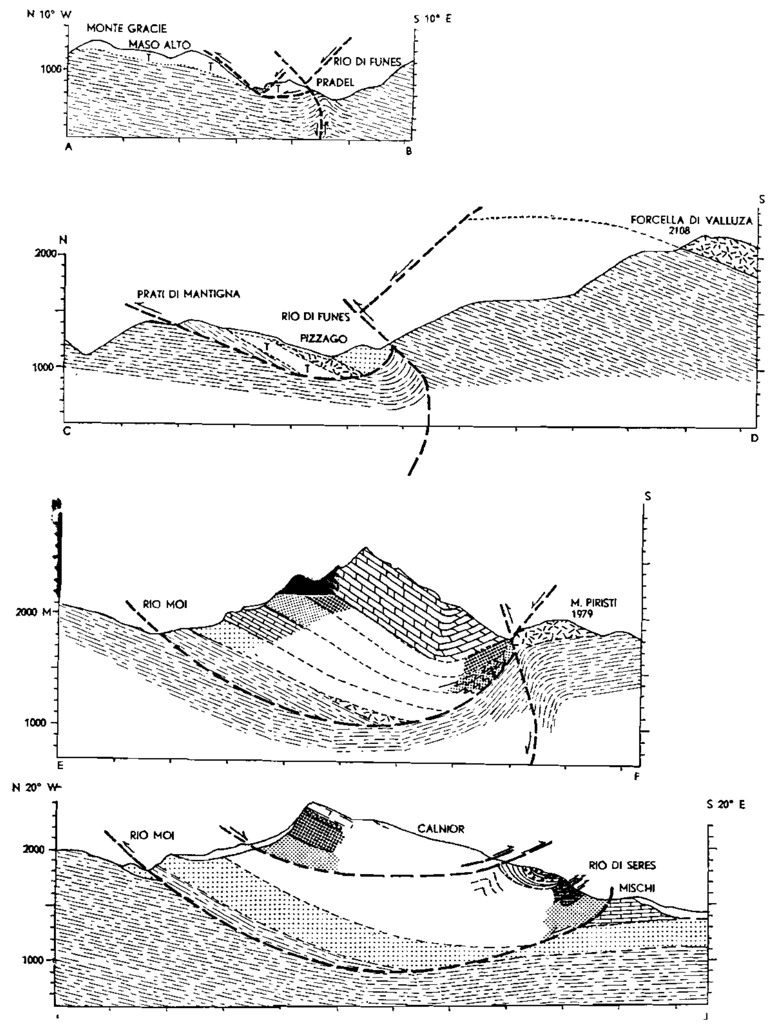

TECTONIC MAP OF THE FUNES ZONE, NW DOLOMITES, N ITALY BY G. B. ENGELEN 1963
UTILIZING THE GEOLOGIC MAPS OF MUTSCHLECHNER (1933), NIJENHUIS (1958, UNPUBLISHED),
AND VAN WAEGENINGH (1961, UNPUBLISHED)
QUARTZ PHYLLITES
QUARTZ PORPHYRY
SCILIAR DOLOMITE
AXIS OF REGIONAL HIGH
ZONE OF REVERSE FAULTS
UPTHRUST
DIAPIRIC CONTACT
NORMAL FAULT, BARBS TOWARDS THE DOWNTHROWN BLOCK
FAULT, POSITION APPROXIMATE
FAULT, CONCEALED
TRANSCURRENT FAULT
FLEXURE
N
CURTAZES
2117
COL VERCIN
AI GINEPRI
1835
TISO
S. PIETRO
PRADEL
CORNO DI PUTIA
2874
M. TULLO
2652
DENTI DI TERRAROSSA
FORCELLA DI PUTIA
S. MADDALENA
M. VILLACCIA
1868
RIO AZZO
SPESSA
M. PIRISTI
1779
VILLA (CAMPILL)
RIO DI SERES
PASSO POMA
COSTA DI GIOVANNI
1764
2303
RASCIESA DI DENTRO
A
B
C
D
E
F
G
H
I
J
K
L
0
1
2
3 km

Fig. 22, a



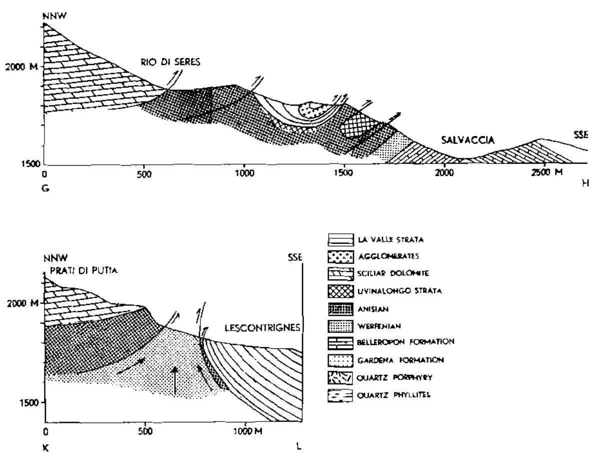




Fig. 22, b Sections of the Funes area, belonging to fig. 22, a. The T in the sections A-B and C-D indicates permian melaphyric tuffs.

the resulting horizontal displacement along these upthrusts is the effect of primary, differentially vertical movements of the basement blocks at depth, and not of a general horizontal compression in the entire layer (Sanford, p. 48, 1959). Moreover, Sanford was able to design analytically by means of the theory of elasticity the stress field for an ideally homogeneous layer, undergoing the same type of distortion (fig. 7b). The stress distribution shows that the deformation will be concentrated mainly in the hinge or fault zone. In the upper part of the rising block almost horizontal tensile stresses are present.

The analytical and experimental situation, as described by Sanford, finds a striking analogy in nature in the tectonics of the Funes line. The only difference is a slight tilt to the south of both blocks, divided by the Funes fault. It does not disturb the analogy of the situation, however, because Sanford (p. 29) stresses that a uniform displacement, superposed on any of the examples will not change the stress distribution.

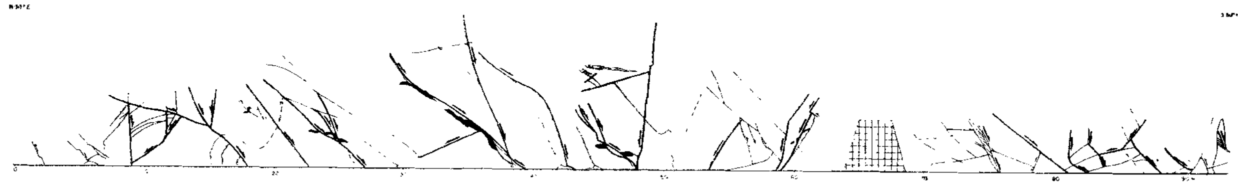


Fig. 22, c Section in the quartz phyllites at the east side of the Isarco Valley, along the road Ponte Gardena - Castelrotto, 500 m S of Ponte Gardena. This section shows mainly normal faulting in the zone of tension S of the Funes fault. Quartz veins are in black, a quartzitic layer is dotted.

The prognosis derived from theory and experiment indicates that the following field evidence might be expected in the crystalline basement-complex:

1. A major normal fault at depth with downthrown northern block.
2. A low-angle northward upthrust north of the main normal fault.
3. A zone of normal, tensional faults, south of the main fault.

The diagnostic observations in the field showed that all these features are actually present in this natural example. The presence of a normal fault in the basement is indicated by the differences in height of the top of the quartz phyllites on either side of the valley of Funes. The top of the phyllites lies at about 2200 m in the mountain ridge south of the Funes Valley, whereas on the same height north of the valley the ladino-carnian Sciliar dolomites of the Putia reef crop out.

In Sanford's experiments thin wedges were thrust forward along the reverse faults over the lower lying surface of the downdropped block. The same happened in the valley of Funes near Spessa, where a similar thin wedge of quartz phyllites was thrust to the north, now lying upon the werfenian calcareous sandstones of the downthrown northern block (see Cornelius-Furlani, 1924, p. 127 and profile 2).

The third phenomenon — a zone of tensional faults south of the Funes line — is exposed in the outcrops of quartz phyllites in the eastern valley wall of the Isarco, 500 m south of Ponte Gardena. In a profile along the railroad many small normal faults to the SSW or NNE are exposed (see fig. 22, c). About 500 m SW of the railroad passage near Chiusa (Klausen) six somewhat larger faults with mylonite zones, dipping 40° - 60° SW were found (Nyenhuis, report Utrecht 1958). The character of one of these faults appeared to be that of a normal tensional fault with downthrow of the northern block according to drag features.

Mittempergher (1962) observed a series of NW-SE and SW-NE striking normal faults with a throw of about 100 m in the quartz porphyries and quartz phyllites near the Alpe Rasciesa di Dentro, south of the Funes Valley. Along the Isarco Valley between Castelrotto and Ponte Gardena a NW-SE trending wedge of quartz porphyries subsided about 50 m. Mittempergher interpreted these structures as relax phenomena at the end of the alpine orogenesis. We think that these faults belong to the faulting mechanism of the Funes fault, because they occur in the zone with tension phenomena south of the latter.

All deformations discussed above affected not only the crystalline basement consisting of slightly southward dipping quartz phyllites, but they had also repercussions in the sedimentary epiderm of permo-triassic rocks which covers the basement blocks. These reactions were purely gravitative, local sliding phenomena, namely:

I. South of the Funes fault a small sheet of permo-triassic rocks glided southwest-ward, to the Gardena Valley over the tilted base. The details of this M. Picio thrust-block will be discussed in the next paragraph VI, 2, b.

II. North of the Funes fault the Sciliar reef mass of the Mt. Tullo-Mt. Putia group glided NNE-ward.

The slide of the M. Tullo-M. Putia group shows the characteristics of a big landslide with in the steep slope, a normal fault at the rear, upthrusts in the lowerlying foreland and wrench faults at the sides (see for instance van Bemmelen, 1955, p. 114, fig. 11, and van Bemmelen 1957, p. 201, fig. 1, f; Seibold, 1955, p. 285; Pierce, 1960). The displacement is greatest at the centre of the slide and becomes smaller to the sides. The mechanism, only on a larger scale, is the same as the base failure or "Swedish break" in soil-mechanics. Failure of the base of a vertical bank along an inclined, curved shear plane will occur when the surcharge exceeds the bearing capacity of the soil beneath the adjacent lower level (fig. 22, a and b). In the natural circumstances presented by the Funes fault, the "vertical bank" was formed by the vertical throw of the fault in the quartz phyllites. The M. Tullo-M. Putia reef mass, lying just above the hinge line between the basement blocks, was tilted to the north and became thus a heavy asymmetrical load on the basement. The quartz phyllites were apparently not able to carry this weight and a spoon-shaped base failure originated below the heavy reef mass.

An elongate strip of basement rocks with the reef atop slid to the NNE along the curved shear plane that cut through the permo-triassic cover and the upper part of the basement. This movement was accompanied by a backward rotation. The imbricate structure of the quartz phyllites north of the M. Tullo-M. Putia group is merely the northern upthrust limit of the block, which slid down from the highest basement block, rotating backward during its movement. The main thrust has a fairly constant distance to the reef (1000 - 1500 m) and secondary thrusts, continuing in east-west direction, splay off where the separation should become too wide at the extremities of the reef mass.

The wedge of Gardena sandstones, intercalated between the quartz phyllites of the frontal thrust plane north of Pradel is a secondary complication. It might result from the sagging down of the upthrust frontal "toe" of the slide block, which broke off by its own weight.

The rapid change in vertical throw along the strike of the Funes fault from 1000 m near Spessa to zero, three kilometers farther east, is the result of:

a) A gradual change from west to east in the primary vertical displacement of the basement along the Funes fault, which decreases from a maximum near the western limit of the block near the Isarco Valley to zero in the neighbourhood of Longiaru (Campil).
b) A secondary displacement, caused by the base failure of the M. Tullo-M. Putia block, which has its maximum throw near the centre of this slide situated north of M. Piristi.

The squeezing out of the plastic Bellerophon and Werfen formations between the rigid reef mass above and the basement below caused some small-scale tectonical complications. A small diapiric dome was thus formed near the southern edge of the reef, east of M. Piristi (see Mutschlechner, 1933 a, profile 11 and fig. 22 a, and b). The anticlinal structure of Passo Poma is the result of diapiric movements of plastic matter, squeezed out from the base of the Putia reef block to the south and from the Sobuccio (the northern rim of the Puez-Gardenaccia-Odle group) to the north.

Another complication was the initiaton of a north-south trending diapiric structure along the eastern edge of the reef mass. The antithetic rotation of the M. Tullo-M. Putia group caused a relative pushing up of its frontal part (the NNE corner of the tilted reefplate). Evidently, after the primary faulting and the erosional dissection of the topography this heavy reef mass was no longer well founded by the underlying plastic Bellerophon and Werfen formations. These formations had a tendency to escape sideward by plastic flow. These movements by squeezing out of the underlying strata caused a NNW-SSE striking vertical normal fault through the M. Tullo-M. Putia group (see fig. 22, a).

A separate movement of the unit in the northeastern corner (containing the M. Putia summit) over the underlying formations was now possible and this frontal block slid backward to the SSE. Small-scale thrusting (fig 22, a and b) of this block over strata in the SE near Longiaru (Campil), refolding of the already previously folded permo-triassic rocks, and accentuation of the diapiric structure along the eastern edge of the reef were the results of the reversed sliding movements of the Putia-block (the eastern part of the M. Tullo-M. Putia group, see enclosed sheets I and II, and chapter VI, 4).

**Summarizing,** it can be said that the present tectonic situation along the Funes fault is the result of a sequence of interrelated tectonic events of decreasing magnitude. In all these events local potential energy was the driving force. Each subsequent link in this chain reaction represents a tectonic feature of decreasing spatial extent and decreasing amount of energy involved. With each tectonic event the potential energy of the affected masses was reduced by means of gravitative sliding or diapiric squeezing away. All movements occurred conformably the general tendency to establish a hydrostatic (= gravitational) equilibrium with a minimum of potential energy (Van Bemmelen, 1931, 1955, 1960 a etc.).

The successive members of this chain of tectonic events of decreasing importance are:

1. Uplift of the geanticlinal core of the eastern Alps in early Tertiary (Oligocene) (van Bemmelen, 1960, a; Agterberg, 1961, p. 132).
2. Development of the normal Pusteria fault with a throw of 6-8 km in the southern limb of the geanticline and intrusion of the Ivigna-Bressanone tonalite along this fault in pre-Miocene (Dietzel, 1960, p. 27; Agterberg, 1961, p. 127).
3. Antithetic movements, accompanying the Pusteria fault caused the Funes fault with a length of 20 km (and also the Tires fault, see chapter VI, 2) and the southward tilting of the basement blocks.
4. The extra load of the M. Tullo-M. Putia reef group caused a NNE-ward sliding along a base failure (Miocene?).
5. The northeastern part of the tilted group—the M. Putia-block—slid backward to the SSE, causing minor folds and upthrusts in the permo-triassic deposits near Longiaru. Probably this phase was late-miocene as the tectonic structure is cut off by the pliocene erosion level of 2000-2100 m east of M. Putia (see chapter IV).

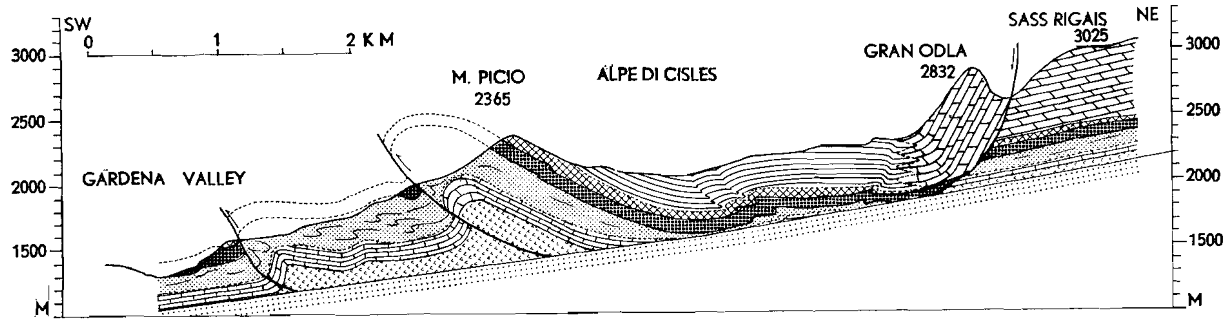


Fig. 23 Section of the M. Picio thrust sheet, SW of the Puez-Gardenaccia-Odle group (Gardena Valley). See for legend the enclosed sheet 1.

## VI, 2, b. THE M. PICIO THRUST SHEET, NORTHEAST OF THE GARDENA VALLEY.

The M. Picio area lies in the upper course of the Gardena Valley, along the western edge of the Puez-Gardenaccia-Odle group. It has been mentioned by several authors.

Reithofer (1928 a) draws a fault east of M. Seceda on his map of the Puez group (see fig. 31). Heissel and Ladurner (1936, p. 31) found a rather important overthrust to the SW south of the M. Picio, which fades out northwestward; werfenian strata are thrust over upper anisian Serla dolomite, Bellerophon limestones over werfenian calcareous shales. They supposed a relation between this structure and the "line of Gardena" ("Grödener Linie") along the south side of the Gardena Valley.

Leonardi (1955 a, p. 57, Tav. 6, fig. 2) called this SW-ward upthrust the "line of Pizza Cuecena", and described it as the broken and upthrust limb between the syncline of Ortisei in the south and the anticline of Pizza Cuecena in the north. He considered these structures on the southern limb of the anticline of Passo Poma (discussed in the preceding subchapter) as features of secondary importance.

None of these authors gave an explanation of the mechanical origin of the observed structural phenomena. Our observations in the field resulted in a rather simple picture which can easily be explained by gravitational sliding.

The southward tilt of the basement block of quartz phyllites between the faults of Funes and Tires (see chapter VI, 2 and VI, 2, a) created favourable conditions for the southwestward décollement of the permo-triassic cover. The tilt of the basement amounted to about 10° S, and the lateral support of the sedimentary cover was removed by the erosion of the Gardena Valley. Consequently a slab of permo-triassic rocks could glide towards the valley floor over the lubricant of gypsiferous Bellerophon strata. The M. Picio upthrust or "line of Pizza Cuecena" forms the frontal limit of this slab which slid to the SSW.

This southward décollement of the M. Picio slab caused at its rear the breaking off of the southwestern edge of the reef mass of the Odle group. The summit of the M. Picio slide block is the Gran Odla (2832 m), which is separated now from the undisturbed Sass Rigais (3025 m) by the gap of Forcella Mezzodi (2597 m); the latter coincides with the normal break-away fault (Pierce, 1960) in the rear of the block. The incipient diapiric structure under the Alpe di Cisles is exposed between M. Picio and Seceda. This structure has been projected into the section of fig. 23, in the direction of its strike.

Parallel to and south of the M. Picio upthrust a similar structure is present near San Christina, though this one is not so well exposed.

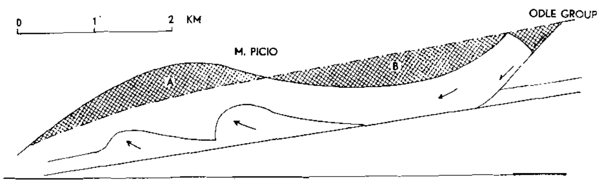
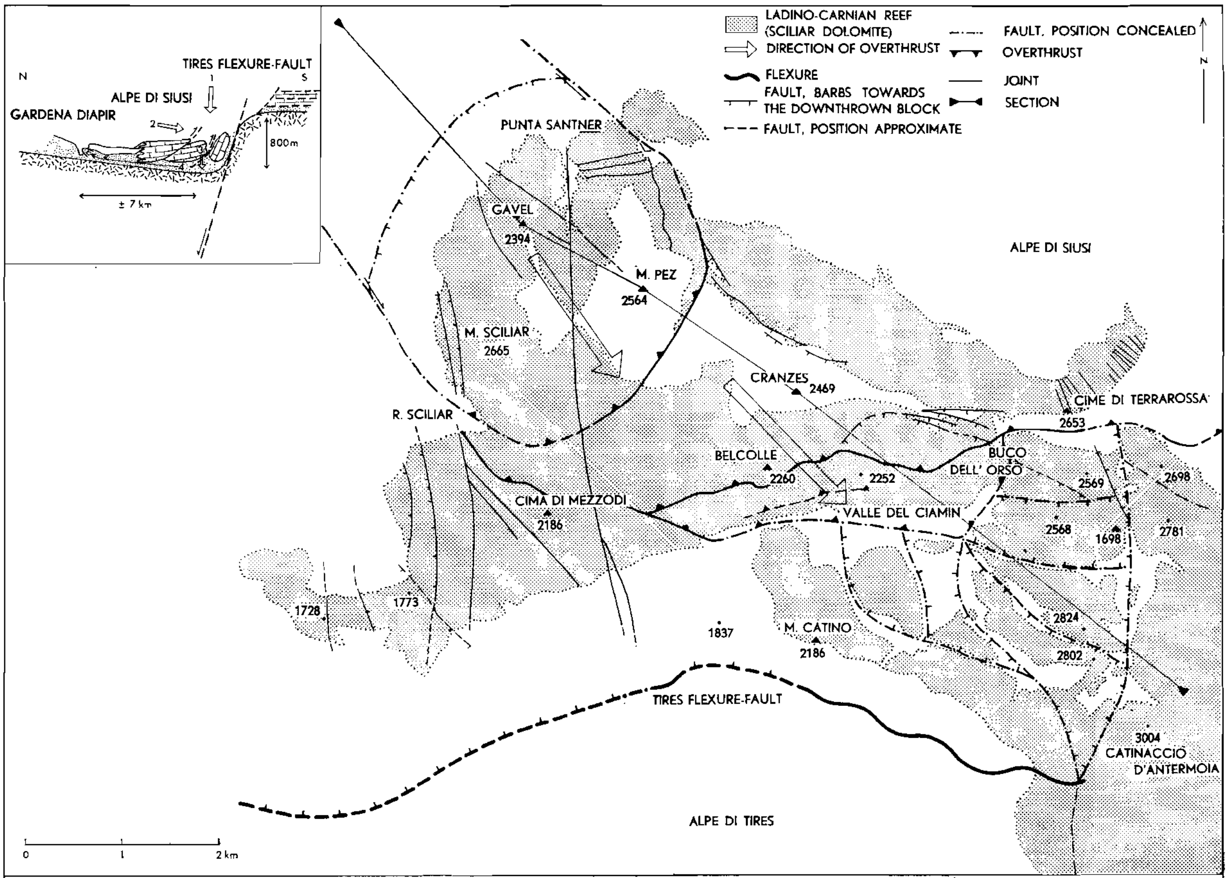


Fig. 24 Scheme of the mass displacements by the M. Picio thrust sheet.

The total volume of the rocks involved in the M. Picio slide can be estimated at 12 cb. km. In fig. 24 the increase of the area of the lower part of the cross section (a) between M. Picio and the base of the slide (the Gardena sandstones) is compensated by a decrease of the area (b) of the upper part of the cross section at the Gran Odla. The former (a) represents an increase in the relief energy (potential energy); however this increase is more than compensated by the decrease of potential energy of the rocks in the Gran Odla at the upper part of the slide block (b). The difference in the balance (b-a) has been used for the plastic deformations and it has then been dissipated (lost) as low-level thermal energy.




TECTONIC MAP OF THE SCILIAR GROUP, NW DOLOMITES, N ITALY

G. B. ENGELEN 1963

UTILIZING THE GEOLOGIC MAPS OF HEISSEL AND LADURNER (1936) AND LEONARDI (1961).

Fig. 25

## VI, 2, c. THE TIRES FAULT WITH THE RELATED TECTONIC PHENOMENA.

A zone of dislocation extends in west-east direction from Bolzano through the lower Isarco Valley to the upper course of the valley of Tires. The character changes from a normal fault near Bolzano into a flexure east of Tires. The northern block subsided and its throw decreases from a maximum in the west (estimated at 700 m) to zero in the Catinaccio group.

Mojsisovics (1879, pp. 127, 131, 181, 182) described this flexured zone in the valley of Tires which separates the flat-lying ridge of quartz-phyllites and its continuation in the nearly horizontal western part of the Catinaccio group south of the "line of Tires", from the Sciliar reef group north of it. The difference in altitude between the base of the lower anisian rocks on either side of the flexure lies within the range of 700-900 m (1400-1500 m and 2200-2300 m respectively).

Von Klebelsberg (1935, p. 376-378) mentions the

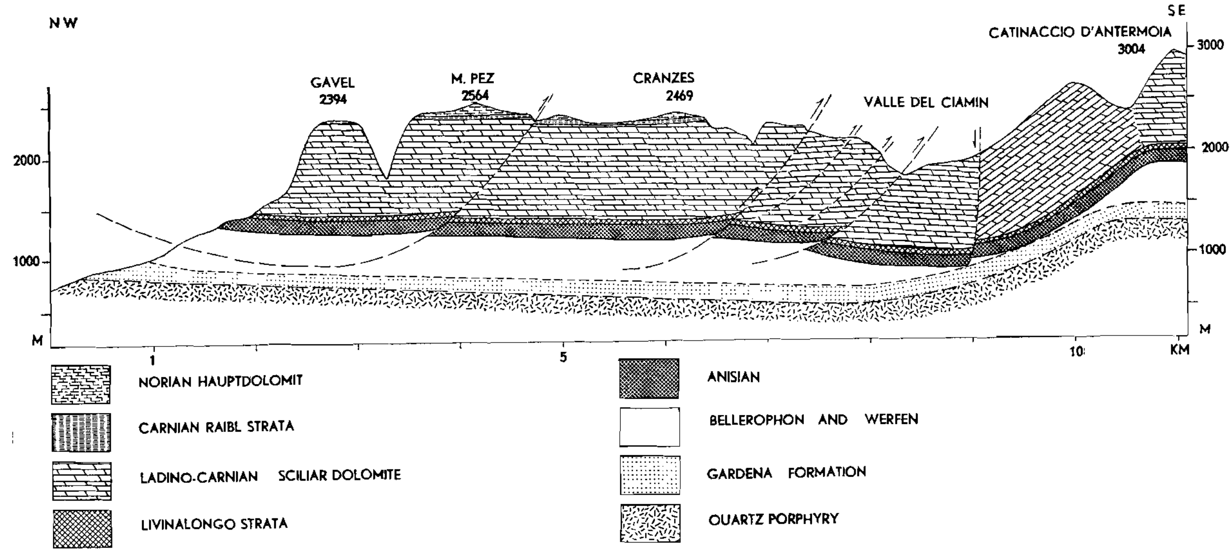



Fig. 26 Section of the Sciliar group. 1. quartz porphyry 2. Gardena formation 3. plastic Bellerophon and Werfen formations 4. Livinalongo strata 5. Sciliar reef dolomite 6. Raibl formation 7 norian Hauptdolomit.

steep northward dip in the strata along the Tires fault, which fades out in smaller dislocations farther east in the Catinaccio group.

Heissel and Ladurner (1936, p. 31) have mapped the area in detail and traced the approximate position of the badly exposed outcrop of the fault. They supposed that the fault disappears in the quarz porphyry west of Tires; this is contradicted, however, by the data collected by Mojsisovics.

Leonardi (1955 a, p. 58) considers the Tires fault in his tectonic scheme of the Dolomites to be an unimportant line of disturbance along the limb between the anticline of Plan to the south and the syncline of Siusi to the north of it. Leonardi regarded it as part of a set of regional tectonic W-E lines that should traverse the entire Dolomites.

To our opinion the Tires fault forms the southern limit of the tilted basement block extending between the E-W Funes fault, the N-S Isarco fault and the E-W Tires flexure-fault. It is an antithetic secondary fault in the pattern of normal faulting of the basement complex, accompanying the great normal Pusteria fault (see V, 2).

Local gravitative adjustments in the permo-triassic epiderm around the hinge line in the basement may be expected here just as in the Funes area described in the preceding subchapter (VI, 2 a). This concept of secondary tectonics gives the clue to a mechanical explanation of the deformations in the triassic strata in the Sciliar group, as well as the "upthrust" in the Gardena Valley ("line of Gardena"). The tectonics of this group have recently been treated in a descriptive way by Leonardi (1962). Leonardi's monograph provides us with an excellent starting point for the interpretation of the mechanics of the tectonics in this group.

The Catinaccio and Sciliar groups once formed a continuous unit. The Sciliar group subsided along the hinge line of the flexure or fault in the basement. Base failure of the escarpment, as observed in the Funes area did not occur here, perhaps because here the throw is less than in the case of the Funes fault. The Sciliar group, however, was slightly tilted to the SSE (estimated at 3-5 degrees), together with the basement of quartz phyllites. On account of this tilt the vertical projection of the centre of gravity of the reef mass shifted to the south and thus the unstable situation of a heavy, tilted reef mass on a plastic substratum came into existence. Consequently, beneath the reef a process of northward squeezing out of mobile Bellerophon and Werfen started. This pressing away of the plastic underlying strata favoured the already existing tendency of the tilted reef to slide toward the lowest part at the base of the hinge line. This complex of gravitational adjustments resulted in the following tectogenetic events (see fig. 25 inset):

I. The diapiric squeezing out of plastic permo-triassic strata in the southern wall of the Gardena Valley, about 6 km north of the Sciliar group (line of Gardena).
II. The settlement of the southeastern border of the Sciliar reef mass at the base of the Tires fault and the south- to SE-ward thrusting, along spoon-shaped fault planes, of the northern and northwestern parts of the group towards this local depression in the SSE.

The details of the formation of the diapir struc-

tures along the Gardena "fault" will be discussed in the next paragraph (VI, 2, d).
Here some details about the second set of movements in the Sciliar group itself will be given.

The Sciliar group can be subdivided into three units with a different type of tectonic deformations:

1) Plastic permo-triassic strata and rigid reef blocks dip steeply north along the Tires flexure-fault.
2) A block-faulted mosaïc of reef blocks is found in the triangle bordered by the Ciamin Valley, the Buco dell' Orso and the Alpe di Tires to the NW, the Tires flexure to the south, and the higher, undisturbed Catinaccio group to the east. The subsidence of the blocks in this triangle was a consequence of the squeezing away of the underlying Bellerophon and werfenian strata towards the Gardena "fault".
3) The central and northwestern parts of the Sciliar reef mass slid SSE-ward to this depressed triangle (2) along spoon-shaped thrust planes. This SSE direction of the décollement was the result of the southward tilt of the basement block and its general eastdip to the centre of the Dolomites (estimated at 5° - 7° and 3° - 5° respectively).

Two thrust blocks can be distinguished: (see fig. 25 and 26).

a). The M. Pez block is a roughly circular unit, limited by a NNW-ward dipping thrust plane which cuts diagonally through the reef mass. The outcrop of the thrust plane can be traced from Punta Santner rising in the northeastern erosional scarp of the Sciliar reef to its greatest height east of Rifugio Bolzano; it descends again through the northern wall of the gorge of the Rio Sciliar. The intersection of the erosional surface with the spoon-shaped base of the slide block cannot exactly be located along the northwestern edge of the reef mass because of the cover of scree. It will have partly the character of internal differential gliding planes, parallel to the strata of the Bellerophon stage and the Werfenian.

3 b). A triangular block, southeast of the M. Pez block, was overthrust by the latter, and the former moved also to the SSE. The thrust plane at its southeastern side extends from the mouth of the canyon of the Rio Sciliar, along the Cima di Mezzodi, through the steep northern wall of the Ciamin Valley to the Alpe di Tires where it fades out farther east.

The thrusting movement of this block was not restricted to this main thrust plane, but it took also place along parallel, secondary planes of movement. These are visible in the northern wall of the valley of Ciamin. Leonardi (1962, p. 62) indicated only one of them to prevent overcrowding of his map. The tensional normal faults in the rear of the thrust block, to be expected theoretically, are actually observed along the northeastern rim of this block.

The time of origin of the Tires basement fault can be dated by means of the preserved rests of erosional levels. The erosional plateau of the Sciliar group lies now at an average altitude of 2400 m. The author considers it as the oligocene level of about 3100 m which sank subsequently 700 m in late oligocene or early miocene time because of the downthrow of the Tires fault-flexure. Remnants of the original oligocene level can be expected only in the western edge of the Catinaccio group, since the eastern part of it was dissected later by the Avisio and its tributaries. Moreover, the group has got a slight eastward dip (3° - 5°) owing to the corresponding tilt of the basement toward the centre of the Dolomites, and it increased somewhat due to the squeezing out of parts of its plastic foundation to the Fassa Valley. The summit ridge with the Catinaccio at 3004 m along the westside of the group is probably the relic of that oligocene level of 3100 m. The post-oligocene erosion caused a lowering of this level. The difference in altitude between the Sciliar plateau and the summit level of the Catinaccio is 700 m, which is about the same as the throw along the Tires flexure-fault measured by Mojsisovics. A late-oligocene age of the Tires and Funes faults would be in accordance with the age of the tonalitic intrusions along the Pusteria fault (Dietzel, 1960, p. 27; Agterberg, 1961, p. 132). Smaller rests of erosional levels in the Catinaccio group within the range of 2400-2500 m, mentioned by Heissel and Ladurner (1936, p. 40) might be correlated with the planation of Aquitanian age in the outcrops of the softer Raibl niveau Nangeroni found in the Sella group (1938).

The next general planation in this area was the pliocene level at 2000 - 2200 m, in the volcanic triassic series around the reefs. The high undulating plateau of the Alpe di Siusi (Seiser Alm) belongs to it. It was probably during this period that the secondary tectonics in the Sciliar group developed (block faulting, squeezing out and upthrusting). It could start only after the removal of a part of the counteracting load of sediments in the "outlet area" near the Gardena Valley, where diapiric movements along the Gardena fault initiated.

## VI, 2, d. THE GARDENA FAULT.

The "Gardena line" is a fault zone which extends along the northern margin of the Alpe di Siusi from Castelrotto to the bottom of the Gardena Valley, between Ortisei and S. Cristina, where it disappears.

Mojsisovics (1879, p. 145) and Ogilvie Gordon (1927, p. 195-197) considered the Gardena line as the outcrop of a normal fault. Heissel and Ladurner (1936, p. 29-31) believed that their data were indicative of a steep northward upthrust instead of a normal fault. They found no indications for a continuation of this upthrust north of the Gardena Valley. In their summaries on the tectonics of the Dolomites, neither Von Klebelsberg (1935) nor Leonardi (1955 a) mentioned the Gardena fault, evidently because they attached to it only a slight regional importance.

Observations of H. Groenewold (1961, report Utrecht) suggested to the author the diapiric character of the deformations along the Gardena line. The genetic relation of this diapiric squeezing out of the plastic strata in the southern flank of the Gardena Valley with the settlement of the Sciliar group to the south of it has already been mentioned in the preceding paragraph (VI, 2, c).

There was only a limited possibility for the escape of mobile matter from beneath the Sciliar reef and the rigid, heavy plate of augite-bearing lavas of the Alpe di Siusi. The dip of the basement to the east prevented diapirism in that direction, because the covering load of sediments increases there in thickness and weight. The throw along the Tires flexure-fault impeded southward directed movements. The general dip of the basement from west to east under the Alpe di Siusi left but one way of escape: squeezing out to the north. It is there that the diapiric movements along the Gardena line are observed at present. Smaller secondary upthrusts, accompanying the main Gardena thrust plane, ly south of M. Bullacia and M. Piz (see Carta geol. delle Dolom. occid. by Leonardi, 1955, and Heissel and Ladurner, 1936).

Summarizing we can say that the movements along the Gardena upthrust were probably the result of the pressure gradient, produced by the load of the Sciliar reef, which acted as the plunger of a hydraulic press system. The pressure could propagate itself to the Gardena Valley in the north at a distance of 6 km under the adjoining rigid cover of the lavas of the Alpe di Siusi.

A depressed zone, occupying Unternon (Heissel and Ladurner, 1936, p. 34) and the upper courses of the Rio del Piz, the Rio di Bulla and the Rio Freddo, fringes the Gardena diapiric structure to the south. This sunken strip reflects the withdrawal of material beneath the Alpe di Siusi and its extrusion along the side of the Gardena Valley. It might be called a "rim syncline" in analogy with salt dome tectonics. The normal fault east of Bagni di Razzes which limits the subsiding Alpe di Siusi to the west fits also in this picture.

This "rim syncline", lying at about 1850-1900 m above sea level, forms an interruption of the pliocene level of about 2000-2200 m. This indicates that the diapiric movements along the Gardena fault are at least partly of post-pliocene age. They probably proceed in the present time in proportion to the progressive incision of the Gardena Valley.

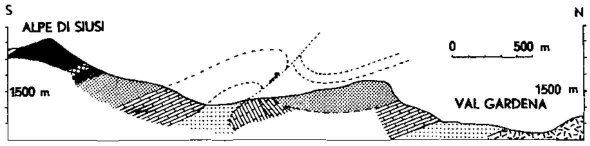



Fig. 27 Composite section of the diapiric "Gardena line" between M. Bullacia and M. Piz (with unedited data of Groenewold, report Utrecht, 1961). 1. Quartz porphyry 2. Gardena formation 3. Bellerophon formation 4. Werfen formation 5. Anisian 6. Livinalongo strata 7. porphyritic lavas 8. La Valle strata.

The profile of fig. 25 and fig. 27 show the essential structure of the "Gardena line" cutting across the subsidiary valley of the Rio Bullacia where the deepest point of the Gardena upthrust is exposed.

## VI, 3. THE NORTHEASTERN DOLOMITES.

Three types of deformations were found in the sedimentary cover of the Dolomites, along their northern border, east of San Vigilio.

a) Folds with E-W axes and steep or overturned southern limbs occur in the upper part of the sedimentary epiderm, which is composed of Hauptdolomit and liassic limestones. The amplitude of the folds diminishes downward.
b) A set of NW-SE striking faults cuts across the E-W folds, being consequently younger than (a). These faults divided the area in a number of blocks which moved to the SW, and formed partly imbricated upthrusts at their south(western) frontal sides.
c) Small, structurally discordant, complicatedly folded and upthrust units of Hauptdolomit, Jurassic, and Cretaceous occur along the faults and on the tilted backs of the dolomite blocks (summit foldings and summit thrusts).

In this subchapter the mechanics of these deformation types, their age, mutual relations and relations with the tectonics of the crystalline basement are discussed.

The greater part of these structures have already been described in papers by Kober (1908), Mutschlechner (1932), Merla (1932), Ogilvie Gordon (1934), Signorini (1951), and others. Our own investigations added only minor data to their observations. However, the concept of the deformation pattern presented here, which is based on the abundantly available geological information, had not previously been recognized. The explanation of

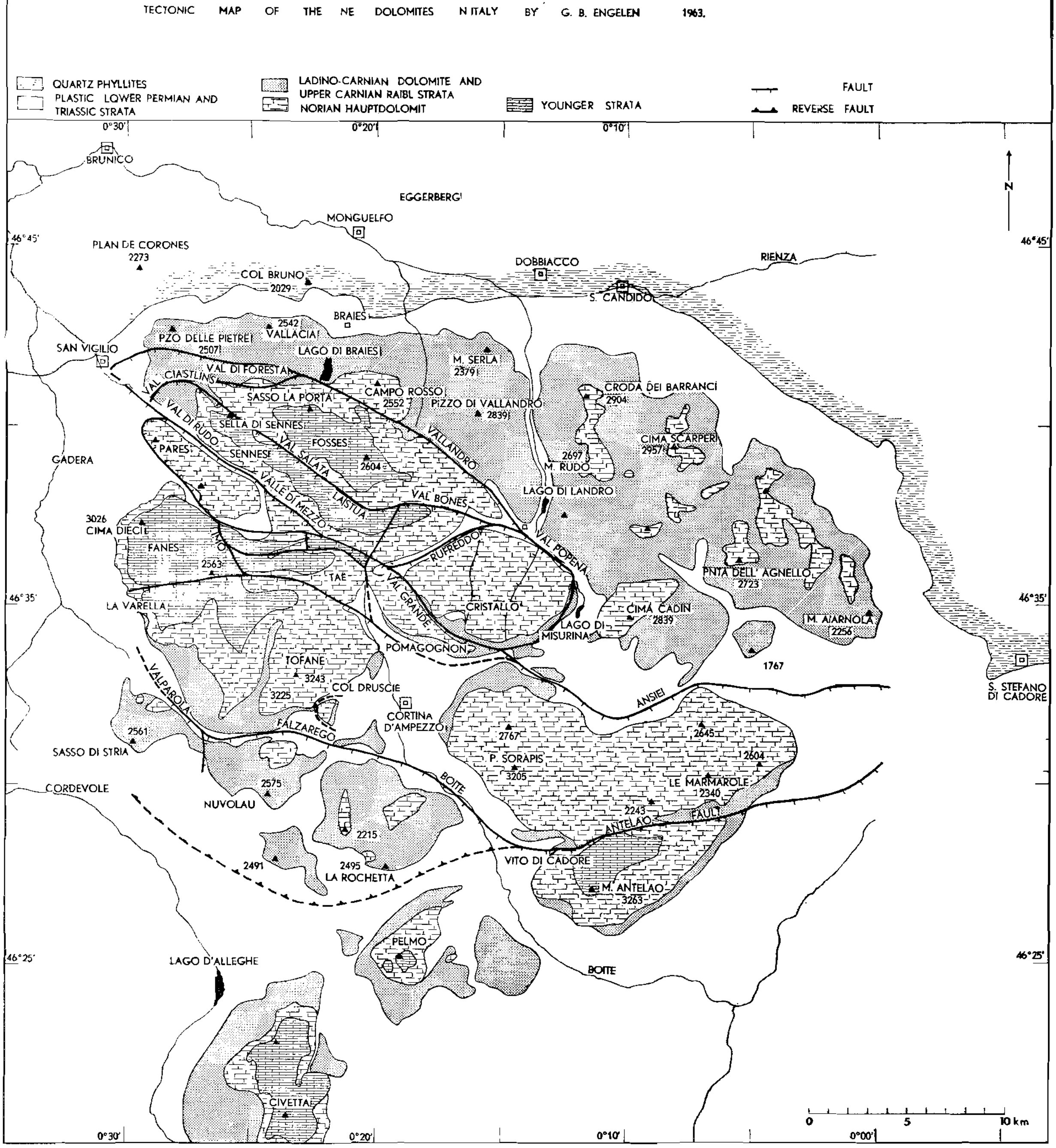



Fig. 28 a

the mechanics of the deformations in this part of the sedimentary cover was greatly stimulated by Agterberg's work (1961) on the tectonics of the crystalline basement, and by the concepts of Signorini (1951), who stressed the importance of gravity tectonics for the area under discussion (see chapter VII, 8).

### (a) The E-W striking fold axes

The Sennes and Fosses groups, SE of San Vigilio, have E-W striking folds with steep or slightly overturned southern limbs. The folds disappear downwards and, moreover, the intensity decreases from N to S. The northernmost of these folds in the Sennes group forms the M. Sella di Sennes fold (2787 m) consisting of Liassic with a core of Hauptdolomit. The other one constitutes the ridge of Col di Lasta (2311 m). Its intensity of folding has decreased considerably; the core of Hauptdolomit is about 400 m lower than in the anticline of the M. Sella di Sennes, 2 km north of it. E-W striking fold axes occur also in the M. Pares block at the M. Pares (2397 m) and N of M. Loires (2526 m), west of Sennes. These folds are less asymmetric and much flatter, because the folds vanish with depth and the M. Pares block represents a deeper stratigraphic level. The anticlinal bend and the northern limb of the fold forming the eastward extension of the anticline of the M. Sella di Sennes (in the Fosses area, east of Sennes) has been removed by erosion; only its steep southern limb is preserved in the Sasso la Porta (2810 m).

The E-W striking folds along the northern border of the Dolomites are most probably due to a southward folding of the well-stratified upper part of the sedimentary epiderm during its décollement from the rising flank of the alpine geanticline in oligocene time.

The folded structure of the M. Sella di Sennes is truncated by a pre-pliocene erosion surface (Merla, 1932, p. 48). It will be the oligo-miocene erosion surface that was also found in other parts of the Dolomites (see also chapter IV).

### (b) The set of NW-SE striking faults

The set of southward, asymmetric and overturned folds is cut off obliquely by a younger set of NW-SE striking faults. The anticlinal structure of the M. Sella di Sennes does not continue into one of these faults — the Val Salata fault — as was supposed by Merla, but it is cut off by the latter (see Mutschlechner's map, 1932).

The whole area between the NW-SE trending anticlinal basement structure of Vallandro (see chapter V, 3) and the Cordevole Valley to the SW (see chapter VII, 6) is divided in a series of elongate thrust slices or fault blocks (fig. 28). The general movement has been southwestward. These tectonics have apparently been caused by and are synchronous with the basement tectonics to the NE of the area. The southwestward, clockwise rotation of the Pusteria fault (see chapter V, 3) brought about the asymmetric anticlinal upwarp of the basement underneath the Vallandro structure; in its turn this deformation of the basement started the faulting and southwestward imbrication in the epiderm of the Dolomites to the SW of it (fig. 20).

The age of the alpine, vertical movements along the Judicaria-Pusteria fault system is oligo-miocene (Dietzel, 1960; Van Hilten, 1960; Agterberg, 1961). The rotation of the eastern part of the Pusteria fault must therefore be younger than oligo-miocene. However, it must be older than late-pliocene because the southwestward imbricated structures in the NE Dolomites (which were induced by this rotation), were truncated by the late pliocene erosion surface (see chapter IV). Thus a miocene or lower pliocene age has to be accepted (a) for the rotation of the Pusteria fault, (b) for the related basement structures of Eggerberg, San Stefano, and Vallandro, and (c) for the set of NW-SE striking faults in the NE Dolomites.

#### The Braies-Vallandro-Val Popena flexure-fault

The uplifted ladino-carnian dolomites on the top of the NW-SE striking Vallandro basement structure are separated from the series of imbricated blocks of Hauptdolomit, Jurassic, and Cretaceous by the flexure-fault of Braies-Vallandro-Val Popena. This fault begins east of San Vigilio in the Val di Fossedura, crosses the pass south of Col Vallaccia at 2250 m, and extends into the Val Foresta. A southern splay starts SE of San Vigilio and extends eastward through the Val Ciastlins over the Cacagnares pass into the Val Foresta, where it joins the main fault. The flexure-fault continues then in SE direction through the depression SW of Campo Rosso in the Valle di Stolla, the Valle di Specie, along Carbonin and through the Val Popena bassa to Misurina. This normal fault changes there into a southeastward upthrust along the base of the Cristallo group. This upthrust forms the connection of the discussed flexure-fault with the next fault of the set, parallel to the latter. The throw of the flexure-fault is maximal along the middle part of the fault near the Alpe di Vallandro, and decreases to the extremities where the fault changes in a flexure. The fault plane dips probably to the SW, in the same direction as the flexured part.

#### The Val Salata-Valbónes-Col Fredo fault

The next fault to the SW, is the Val Salata-Valbónes-Col Fredo fault. Beginning at the NW-side in the Val di Fossedura, it separates the Fosses block from the Sennes block, then crosses the Passo Col Fredo, and joins the Braies-Vallandro-Val Popena flexure-fault near Carbonin. Mutschlechner (1932, p. 234) found a throw of 400 m for the subsided SW-block (Sennes) along the 60° - 70° NE dipping fault plane. Minor, secondary complications (partly of gravitative character) accompany the fault in the more plastic Jurassic and Cretaceous of La Stua and the Col Fredo.

#### The Valle di Rudo-Valle di Mezzo-Val Grande fault

The next fault to the SW runs through the steepsided Valle di Rudo, the lower Valle di Mezzo, and the Val Grande to the southern side of the Christallo group. It is a vertical or steeply SW dipping normal fault with the SW-side down. Its throw could not be measured exactly, but it probably amounts to some hundreds of meters. A smaller NW-SE striking, oblique fault (coinciding with the Rufreddo Valley between Podestagno and Carbonin) separates the more deeply subsided Cristallo group in the SE from the Sennes and Fosses groups to the NW. The three blocks form together a major, about 7 km wide, NW-SE striking slice of the sedimentary cover, which subsided and tilted to the NE. The Valle di Rudo-Valle di Mezzo-Val Grande fault extends still farther eastward, along the north side of the Sorapis and Marmarole groups through the Ansiei Valley and the small Val Pian di Sera into the permo-triassic anticline west of Auronzo, which was thrust southward (see Agterberg, 1961, p. 69).

### The Pares-Limo-Val di Fiorenza fault

The next NW-SE striking fault zone consists of some minor lozenge-shaped blocks, separated by faults oblique to the strike of the zone: the M. Pares block, the Croda d'Antrouilles block, the Antrouilles block, and the Taë-Pomagognon block. The Pares-Limo-Val di Fiorenza fault probably continues in the anticlinal structure formed by the plastic San Cassiano strata between the Cristallo and Sorapis groups: it then joins the Valle di Rudo-Valle di Mezzo-Val Grande fault.

In general, this zone shows the same pattern of SW-ward imbricated blocks, but it is somewhat complicated in the NW-end by the northwestward squeezing out of the underlying plastic Permo-Triassic towards the Dolomites of San Vigilio and San Martino (see chapter VI, 2 and fig. 29). On account of this process the M. Pares block sank most at its northern corner, and the SE corner tilted upward. In this way potential space became available between the southeastern lower side of the dolomitic M. Pares block and the underlying quartz-phyllitic basement. The plastic Permo-Triassic between these rigid stratigraphic units was under load pressure caused by the overlying pile of dolomites. It flowed from the adjacent Antrouilles block to this potential "void", thus forming the upward bulge of Permo-Triassic below its dolomitic cover at the southeastern end of the M. Pares block. The Antrouilles block southeast of it subsided deeply as a volumetric compensation for the upward movements under the SE corner of the M. Pares block. Because of these differential vertical movements the Sciliar dolomite crops out in the upper Valle di Rudo at 2000 m, whereas at only 5 km distance, cretaceous strata occur at 1500 m above sea-level near Antrouilles.

### The Valparola-Falzarego-Boite-Antelao fault

The southwestern side is thrown down as seen in all major faults of the discussed set of NW-SE striking faults. A throw of 400 - 500 m occurs along the NW part of the fault. The more or less vertical fault at the NW extremity changes into a steeply N and NE dipping reverse fault between the Sorapis-Marmarole and the Antelao blocks. The belt to the NE of this fault is composed of three major blocks: Fanes, Tofane and Sorapis-Marmarole.

The Fanes group — the block at the NW end of the zone — was deformed into a saucer with steeply upward tilted edges. This relative subsidence of its centre was caused by the northwestward squeezing out of its plastic permo-triassic base towards the Dolomites of San Vigilio and San Martino (see chapter VI, 4 and fig. 29). The edges dip 60° or more towards the centre. A huge slump of liassic blocks occurred along its southern side towards the depressed centre.

The oblique fault between the Fanes saucer and the Tofane block extends from the Sella di Varella along la Stiga (2769 m) and M. Varella (2562 m) to the Pares-Limo-Val Fiorentina fault. This fault is complicated by secondary tectogenesis along its strike, owing to southward gliding of the Jurassic and Cretaceous along the fault scarp, south of M. Varella.

The Tofane and Sorapis-Marmarole blocks within this major zone are divided into smaller blocks, which are oblique or normal to the strike of the zone.

The southernmost zone of dolomite blocks is composed of the Sasso di Stria, the Nuvolau, and the Croda da Lago-Rochetta units. This elongate zone is bounded to the SW by the complicated SW and S-ward thrust structures occurring in the plastic Permo-Triassic in front of this zone (see the chapters VII, 6 and VII, 8). These deformations (with direction of tectonic transport normal to the southern and southwestern edges of the dolomite blocks) were brought about by the subsidence of the latter into their plastic base. The SW-ward directed squeezing out of the plastic matter was due to this local field of potential energy. This folded and upthrust belt joins onto the Antelao fault near S. Vito di Cadore.

### (c) Small, discordant, complicatedly folded and upthrust units

Phenomena of gravity tectonics at a restricted scale are often found in the discussed area, for instance:

1) the subsidence and southward movement of an elongate strip of dolomite with upthrusts in front, at the southern margin of the Cristallo group;
2) the eastward sliding of the small Col Druscié

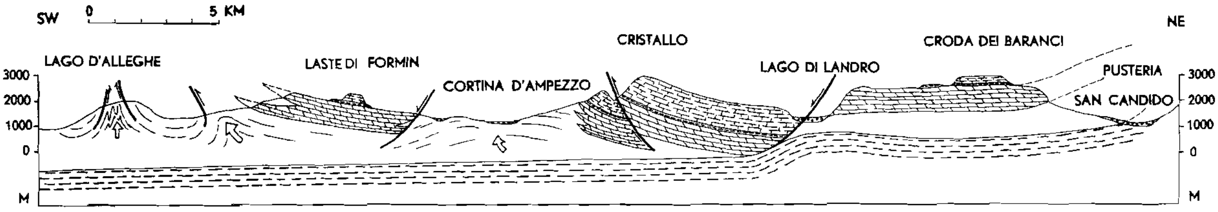



Fig. 28, b Schematic section of the NE Dolomites, see for legend fig 28, a.

block towards the glacially accentuated basin of Cortina d'Ampezzo in the Boite Valley;

3) gravitative reactions of the upper part of the sedimentary column along the faults between the dolomite blocks; the faulted dolomites were tilted and the more plastic younger strata slid down from these slopes. These very complicated, local, minor tectonics were correctly interpreted and elucidated as the effects of gravity tectonics by Accordi (1955, 1957).

The E-W striking tectonic directions in the Dolomites east of the Boite Valley curve gradually into the NW-SE striking fault system lying west of this valley and SW of the anticlinal basement structures of San Stefano and Vallandro. The almost north to south trending belt of ladino-carnian volcanics along the Gadera and Cordevole rivers forms the boundary between the western and the eastern Dolomites. This zone reacted plastically to the stress field. It could not transfer the compressive stresses to the SW acting in the competent sheet of dolomites of the northeastern Dolomites (see chapter III, 2). Consequently the Sasso Lungo, Sella, Puez-Gardenaccia, and Marmolada groups were not affected by this more regional, compressive stress field of gravitative origin governing the tectogenesis in the NE Dolomites. Thus, in the NW Dolomites the tectogenesis resulted from the more local stress fields arising from the young cenozoic differential erosion (see chapter VII).

## VI, 4. THE DOLOMITES OF SAN VIGILIO AND SAN MARTINO.
(see sheets 1, 2 and 3)

The high NW rim of the Dolomites consisting in its upper parts of Sciliar dolomite and Hauptdolomit has an indenture south of Brunico (fig. 29). Very contorted permian and triassic, plastic strata are exposed in this indenture, which has an area of about 100 sq. km. The low-lying surface (1400 - 1900 m) is surrounded by high dolomite masses at three sides: the Sennes and Fanes groups to the east and southeast, the Puez-Gardenaccia-Odle group to the southwest, and the M. Tullo-M. Putia group to the west. The northern boundary of the area is formed by the quartz phyllites of the crystalline basement rising northward.

The easily erosible La Valle and San Cassiano strata were deposited in ladino-carnian time in the present low area of the Dolomites of San Vigilio and San Martino. This primary sedimentary facies anomaly is reflected in the course of the high rim of the Dolomites.

The area under discussion was described by Ogilvie Gordon (1927) and Mutschlechner (1932). Studies on the adjacent groups were made by Kober (1908), Merla (1932), Reithofer (1928 a), and Mutschlechner (1933).

It was possible to disentangle the complicated tectonic structures by very detailed mapping (partly on scale 1 : 100) and analyses of the deformation phenomena by means of the prognosis-diagnosis method (Van Bemmelen, 1960 b). No indications for a tectonic development by regional, alpine compressive stresses were found, as was assumed by previous authors. The tectonic phenomena appeared to be mainly gravitative reactions to the rise of the alpine geanticline since early tertiary time and local gravitative adjustments to the relief energy produced by selective erosion in young cenozoic time. The oldest folds, however, are probably of cretaceous age.

Five distinct tectonic directions were found, some of them are superposed. They can be divided in two groups: an oldest stage with more regional, west-east striking fold axes and four younger stages with more local NE-SW, NW-SE, N-S, and NNE-SSW striking fold axes.

The oldest folds in the plastic Permo-Triassic of the Dolomites of San Vigilio and San Martino are steep or slightly overturned to the north with east-west striking axes. In most cases their horizontal axes were tilted later by superposed folding.

These oldest, northward directed folds might have come into existence during the older, Gosau phase of alpine tectogenesis. During that phase there was a northward flow of matter from a rising tumor in the south in the northern part of the Adriatic towards a foredeep in the north (the Tauern foredeep; see Van Bemmelen, 1960 a). This northward movement caused the formation of the austrian nappes. Although during that phase the sedimentary epiderm of the Dolomites was transported northward more or less passively on the basement of quartz phyllites, it is quite possible that the slight northward tilt towards the northern foredeep caused some northward sliding in that epiderm.

Somewhat farther north, in the Brenner area, these northward sliding movements caused the thrusting of the Carboniferous Strata of the Steinacher Joch nappe over the Permo-Triassic. Later, in cenozoic time, there was a major primary tectonic reversal of the relief; the Tauern foredeep was arched up into the present alpine geanticline, whereas the former Adria-tumor collapsed and subsided, being now buried under the Venetian Plain and the northern Adriatic sea.

The cretaceous conglomerates on the top of the Sella plateau (see chapter III, I) are interesting in relation with Van Bemmelen's concept. The presence of the quartz pebbles cannot be explained by a supply from within the Dolomites, and the high degree of roundness of the components suggests more than local transport. Supply from the marine environment in the north is also improbable, but these conglomerates might be the erosion products of the assumed Adria-tumor to the south.

The younger, more local directions of the tectonic deformations in the Dolomites of San Vigilio and San Martino were formed in miocene and younger time, when the reef masses began to subside and to squeeze out their mobile permo-triassic base towards the surrounding valleys. The individual directions of these tectonic deformations are normal to the edges of the subsiding blocks and they decrease in intensity with the distance from the blocks. As the subsiding movements were not fully synchronous superposed folding was the result.

The five sets of tectonic directions are discussed below:

### (1) Northward movements:

Near the confluence of the Rio di Campil with the Gadera undisturbed northward folds in upper Bellerophon limestones are exposed (see Agterberg, 1961, photograph 16). Chevron folds in the Livinalongo strata and isoclinal folds in the Anisian are visible farther south in the Badia Valley, west of the bridge at Pederoa (see sheet 3, profiles 8 and 9). In this locality their east-west striking axes dip steeply (60°) westward. These axes have been tilted by the younger diapiric, upward extrusions and folding in a zone along the incision of the Gadera Valley.

The anticline of Pederoa-Badia is a diapiric box-fold, about 3 km wide, with an east-west axis. It probably belongs also to this oldest stage of cretaceous deformations (see sheet 2, profile M-N). The fold was refolded and accentuated in a later stage. The Pederoa-Badia anticline extends westward into the anticline of Passo Poma, south of the M. Tullo-M. Putia group. The latter is a secondary deformation of the sedimentary epiderm parallel to the normal faulting along the Funes fault (see chapter VI, 2, a).

The Pederoa-Badia anticline fades out eastward in the valley of La Valle. We did not find a single indication for a continuation of this anticline farther eastward as an extension of the Funes line. The Funes fault proper — a complicated normal fault — ends at the Passo Poma. The diapiric anticline of Pederoa-Badia is situated due east of it but this structure was caused by quite different processes of gravity tectonics, as has been pointed out in the foregoing paragraph. The faults through the Fanes group, still farther east which were considered as an eastward extension of the Funes fault appear to belong to a set of SW-ward upthrusts which again belong to another stress field (see chapter VI, 3).

The following reasons can be given for the concept that the folds with E-W striking axes are the oldest among the five sets of fold axes:

1. The folds are covered by sediments of higher stratigraphic levels which are folded along NE-SW axes, for instance east of the Col Vercin.
2. The NE-SW axes are older than the NNE-SSW striking fold axes east of the M. Tullo-M. Putia group, because the former are refolded by the latter.
3. The NE-SW axes are refolded by the NW-SE striking folds northeast of the Puez-Gardenaccia-Odle group and they are consequently older.
4. The folds with E-W axes are influenced by tectonic structures with N-S directions, as appears in the following cases:

a) The east-west striking axes near Pederoa dip in opposite directions on either side of the Gadera, which is followed by a N-S striking anticlinal axis.
b) The anticline of Pederoa-Badia with E-W axis shows a characteristic outcrop pattern of the lower Werfenian, which indicates its refolding along N-S axes (see for outcrop patterns of superposed fold systems Carey, 1962 b, fig. 18).
c) The Bellerophon limestones with E-W axes along the road 1500 m south of San Martino are cut off by a N-S striking wedge of werfenian strata (see sheet 3, profile 10).

Thus it appears that all other directions of tectogenesis deform the E-W trending fold axes. On the other hand, these other structures were nowhere refolded along E-W axes. This is a double check

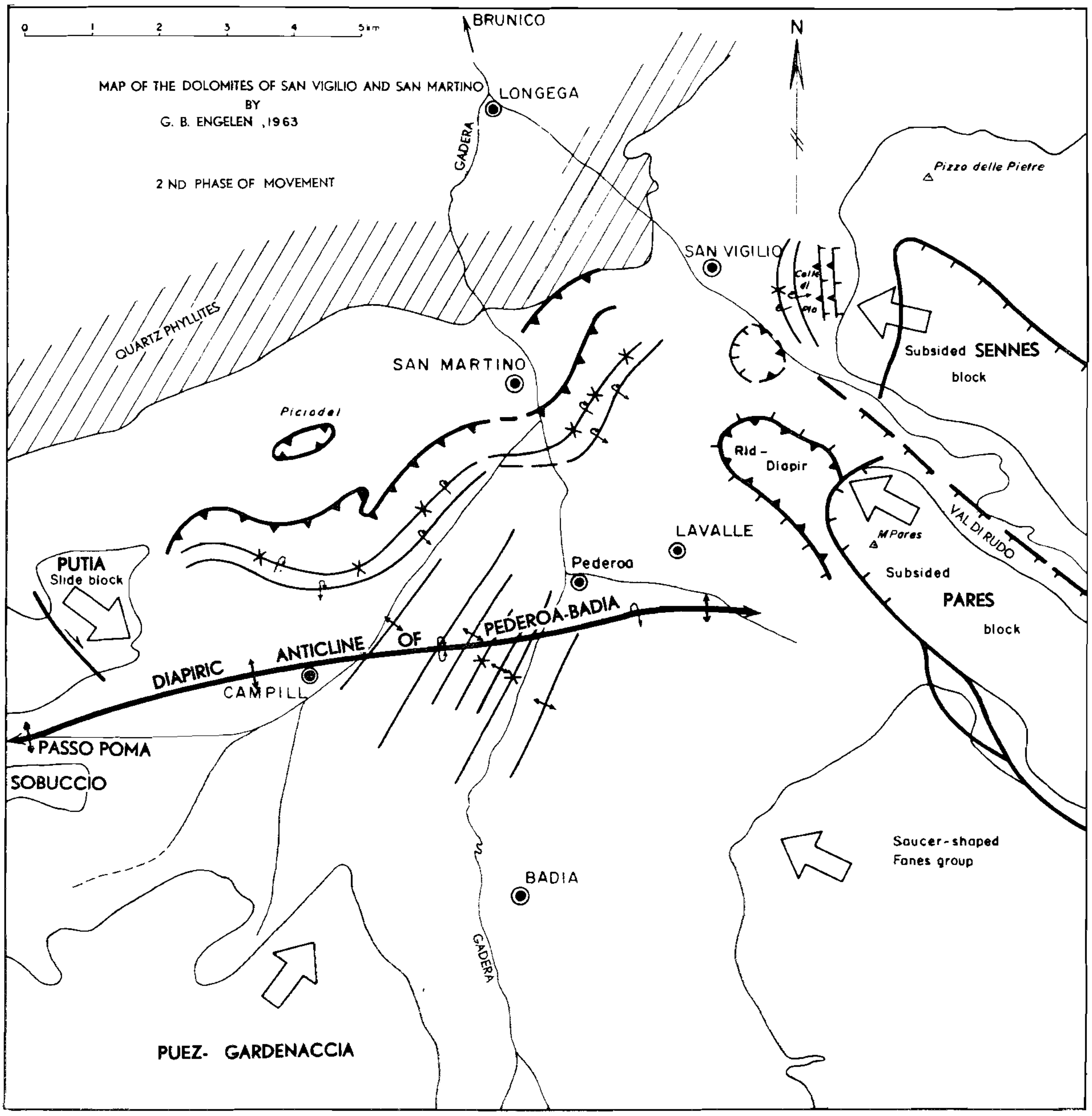



Fig. 29

for the supposition that the E-W axes are the oldest set of deformations.
A cretaceous age was already suggested in the foregoing paragraphs for this oldest set.

**(2) Northwestward movements:**
The Dolomites east of San Vigilio were faulted during the Miocene — lower Pliocene by a set of parallel NW - SE striking faults into elongate blocks, which slid southwestward (see chapter VI, 3).

The plastic Permo-Triassic beneath the northwestern edge of one of these blocks, the Sennes unit, was pressed to the NW and W towards the valley of San Vigilio. The imbrications and recumbent folds with a core of gypsum of the Colle di Pla area were the result (see sheet 2, profiles A-B and C-D).

The elongate M. Pares unit between the La Valle and San Vigilio area belongs to the set of subsided blocks too. This 7 km long and 1,5-2 km wide block largely subsided along its NW corner where Norian comes into contact with Werfenian. Only 400 m is exposed of the total thickness of 1000 m that is found at the right side of the Valle di Rudo — the continuation of the valley of San Vigilio. This means that a subsidence of 600 m at the NW corner of the block is probable. Already Mutschlechner (1932, p. 236) suggested a subsidence of the M. Pares unit, but he did not realize that this process implies a volumetric compensation. Thus the oval-shaped thrust plane in the plastic Triassic in front of the NW edge of the M. Pares block was not yet recognized by him as the overthrust edge of a mushroom-shaped asymmetric diapir (the Rid-diapir), which was pushed up as a volumetric compensation by the subsiding block (see sheet 2, profiles E-F and G-H).

Apart from this diapir the squeezing out of matter to the NW resulted also in some other structures:

1) The Bellerophon an Werfen formations between the diapir and the frame of quartz phyllites to the north were folded in minor NW-ward directed folds.

2) Some large recumbent folds with NE-SW axes were formed in the Werfenian (see sheet 2, profiles E-F and G-H).

3) The anticlinal core of one of those recumbent folds was sheared off and slid from the Col Vercin area northward, down the topographic slope. The outlier at Piciodel with its inverse stratigraphic succession west of San Martino is a relic of it. The rootzone of this mass, described by Mutschlechner (1933, p. 96) as a rootless "Klippe", appears to crop out in the steep valley side of a tributary rivulet of the Rio di Bicocca, south of the Col Vercin, where almost horizontal wedges of Anisian and lower Werfenian are found between upper Werfenian (see sheet 2, profiles O-P and U-V). The folds were refolded later by the sideward push of the M. Putia mass, which slid to the SE (see chapter VI, 2, a). The recumbent folds of the Col Vercin area extend eastward in those east of the Gadera Valley, which are situated in front of the Rid-diapir.

4) Thrusting to the NW was observed along the stratigraphic boundaries between the Gardena formation and the lubricating lower Bellerophon gypsum, between the lower and upper Bellerophon strata, and the upper Bellerophon and Siusi strata.

5) A part of the updomed rocks in front of the Rid-diapir slid NE-ward to the Valley of San Vigilio along a listric faultplane (see sheet 1 and sheet 2, profile G-H).

The area south and west of the Valley of La Valle was not influenced by the subsidence of the M. Pares unit, but by the subsidence of the adjacent Fanes group to the SE, which sank more or less simultaneously with the M. Pares block and deformed at the same time into a circular saucer-shaped mass with steep edges (see chapter VI, 3). The NNE-SSW fold axes in front of it merge into the NE-SW axes farther north. The folds of this stage are still visible in the outcrop pattern within the east-west striking, large anticline of Pederoa-Badia.

### (3) Northeastward movements:

Good outcrops of folded Triassic are observed along the road along the Gadera between Pederoa and Badia. They provide a cross section of the anticline of Pederoa-Badia (see fig. 30 and sheet 3, profiles 1, 2, 3, 4, 5, 6, 7). The intensity of the deformations by northeastward movements decreases from south to north. An imbricated and folded series of La Valle strata is exposed where the road crosses the Gadera, 1 km north of Badia. To the north follow successively: a small diapiric exposure of Livinalongo strata, cascading folds in Livinalongo and La Valle strata, Anisian, and upper Werfenian, a diapir of lower Werfenian and finally a series of cascading folds in upper Werfenian.

The younger complications in the southern limb of the diapiric box fold of Pederoa-Badia fade out to its central part. Here the youngest, steep folds with N-S striking axes dominate. The NW-SE axes of the cascading folds of the third stage were refolded along a N-S axis and their axes were tilted to the NW and SE on either side of it. The imbrication, diapirism and cascading folds were caused by the subsidence of the Puez-Gardenaccia reef in the SW and the northeastward squeezing out of the plastic lower triassic strata.

The structure west of the Gadera between the box fold and the Puez-Gardenaccia group is badly exposed, but it seems to be a somewhat imbricated, isoclinal syncline, dipping steeply to the SW. Its northeastern limb is the partly southward overturned limb of the anticline of Pederoa-Badia. The normal faults at Col da Oi belong to young-cenozoic landslides.

### (4) East- and westward movements:

The youngest deformations are closely related to the deep incision of the Badia Valley by the Gadera. They consist of a compressed wedge (see sheet 3, profile 10) and steep-limbed folds with vertical axial planes and a N-S strike. They occur at both sides and parallel to the river. The intensity of the deformation decreases to zero within a distance of 1 - 2 km normal to the river. The removal of load by the erosion of the valley induced an elongate, local field of compressive stresses directed towards the valley floor. The material in the valley sides was pressed towards the "void" of the valley and is deformed into N-S striking folds. The N-S folds are still very steep in the entrance of the gorge of the Rio di Armentara, between Pederoa and Badia, but they die out eastward so that 1½ km farther east only minor folds are exposed in the Anisian of the steep scarp Col al Cogn. The same confluence of matter caused the compression of the wedge of lower Werfenian, exposed 2 km north of Pederoa.

**(5) Southeastward movements:**

Folds of this stage are found at the west side of the area, between San Martino and the east side of the M. Tullo-M. Putia group. The eastern part of that group slid to the SE (see chapter VI, 1, a), which resulted in three types of deformations:

a) an intense S and SE-ward folding and upthrusting in the Permo-Triassic along the northern side of the Valley of Campil;

b) the rise of a small diapir of Werfenian between the M. Putia and the Col Vercin;

c) the refolding along NNE-SSW axes of the older folds in the Col Vercin area.

The structures of this stage are truncated by the upper pliocene erosion surface, which is evidence that they are older. The refolded axes of the second stage are still older, probably of mio- or pliocene age, because they are younger than the oligo-miocene erosion level which preceded the set of NW-SE faults east of San Vigilio. As the folds of the fifth stage refolded the second set and as they are pre- late pliocene they are of a mio- or pliocene age.

The gravitative movements in the Dolomites of San Vigilio and San Martino still proceed in the present. The steep slopes of the valleys of Badia, San Vigilio, Campil and La Valle show many signs of slumping and sliding, which is evident from the distortion of fences, breaks in the vegetation cover, marshy spots etc. These movements of creep and slumping are not merely the adjustments of the slopes to the vertical erosion; they are probably also the effects of a lateral transport of matter through the mountain to the valley sides.

The plastic matter of the latter is continually pushed to the valley and the sides of the valley are oversteepened by this internal supply of rocks. During this process the valley floor is not much lowered because the river is almost overburdened by the task of removing the matter that accrues to it through the valley flanks.

# CHAPTER VII

# THE GRAVITY TECTONICS IN THE SEDIMENTARY EPIDERM INDUCED BY EROSION, INDEPENDENT OF PRIMARY TECTONIC DEFORMATIONS OF THE BASEMENT

## VII, 1. THE PUEZ-GARDENACCIA-ODLE GROUP.

The mountain group of the high plateaus of Puez and Gardenaccia forms together with the Odle group to the northwest a separate entity in the landscape of the northwestern Dolomites. The valleys of Funes, Longiaru (Campill), Gardena and Badia surround this mountain complex.
The outcropping sediments range from the permian Gardena sandstones at the base to the cretaceous marls on the high plateaus (fig. 31).

Trautwein (1920) has studied the Odle group, Reithofer (1928 a) published a monograph with accompanying map on 25.000 scale of the Puez-Gardenaccia group. Some aspects of the tectonics of this complex have been described by Ogilvie Gordon (1927), Heissel and Ladurner (1936), Leonardi (1955), and Accordi (1955). Accordi investigated in great detail the so-called "summit foldings" ("Gipfelfaltung") on the high plateaus and has given a very attractive interpretation of these formations applying the concept of gravitative glide tectonics.

Combining all these data with the unpublished survey by Groenewold (report Utrecht, 1961) and the results of our own investigations, it was possible to trace the tectonic history of the area. It appears that the mechanics of the tectogenesis can only be understood when gravity is considered as the main driving force. Local fields of potential energy have been created during the erosional history of this area, and this energy gave rise to tectogenetic reactions of sliding, subsidence, tilting and hydraulic processes of diapirism.

The group has an elongate, saucer-shaped form with a SW-NE striking axis. The centre is composed of the almost horizontal, ladinian, dolomitic reef, which is separated by the marly, dolomitic or silty Raibl strata from the overlying, capping, norian Hauptdolomit (thickness 200-360 m). On the norian dolomites some isolated outcrops of jurassic limestones and cretaceous marls with a maximum thickness of 10 m occur, which are cut by an oligocene erosion level at 2250-2650 m (see chapter IV, 1).
In the deep valleys around this mountain-complex outcrops of permo-triassic, sedimentary and volcanic rocks are found, which are greatly disturbed.

The northwestern part of the complex (Odle) lies on the eastside of the tilted basement block of Funes, which at that place plunges to the SE. This plunge caused part of the dip of 25° to the SE of the Odle group and was also the primary cause for the sliding of the M.Picio sheet to the SSW (see VI, 2, b) All other tectonic features, however, can be explained by gravity tectonics due to the local field of potential energy inside of this mountain group. No interference of regional, tangential stresses or other influences of the basement have to be accepted.

The leading principle for the understanding of the structural deformation of this group is again the sinking of the relatively heavy, rigid reef into its plastic substratum of gypsiferous and argillaceous Permo-Triassic. These strata were squeezed out from its base towards the encircling valleys, where they emerge as diapiric structures of strongly contorted rocks. The outward flow of matter under the group caused the subsidence of its centre, its saucer-shaped form, and its disintegration into a number of blocks. At the same time diapiric anticlines with centrifugal direction bulged up in the surrounding valley sides at the base of the reef.

This saucer-shape of the central part created suitable circumstances for another gravitational reaction: the sliding of the strata above the plastic Raibl from the tilted edges of the reef towards its depressed centre. Thus the summit foldings on the undisturbed surface of the central region came into being. All observed structural phenomena can thus be elucidated as the effects of a foundering circuit as was described in chapter I (namely subsidence of the denser reefs, causing saucers with centrifugal diapirism at their base and centripetal gravity sliding at their top).
These structures are discussed now:

**Summit foldings**

In the excellent study of Accordi (1955) almost every feature concerning the summit foldings on the Puez-Gardenaccia plateaus was recorded.
Small thrust masses of Hauptdolomit ("Klippen") occur on isolated peaks of jurassic and cretaceous rocks (the Punte del Puez, the Col de Muntijela, the Col da la Sonè and the Cuècenes). These "Klippen" consist of one to three slices of norian dolomites, which slid down a topographic slope from the NE, meanwhile partly crumpling themselves, and folding and fracturing the underlying jurassic and cretaceous rocks. Accordi unraveled these "thrust masses" as the relics of gravitative décollement from the top of the complicated bulge of triassic

TECTONIC MAP OF THE PUEZ-GARDENACCIA-ODLE GROUP, NW DOLOMITES N ITALY BY G B. ENGELEN, 1963 UTILIZING THE GEOLOGIC MAPS OF TRAUTWEIN (1920), REITHOFER (1928), OGILVIE GORDON (1927), HEISSEL AND LADURNER (1936), LEONARDI (1955), ACCORDI (1955) AND GROENEWOLD (1961, UNEDITED)

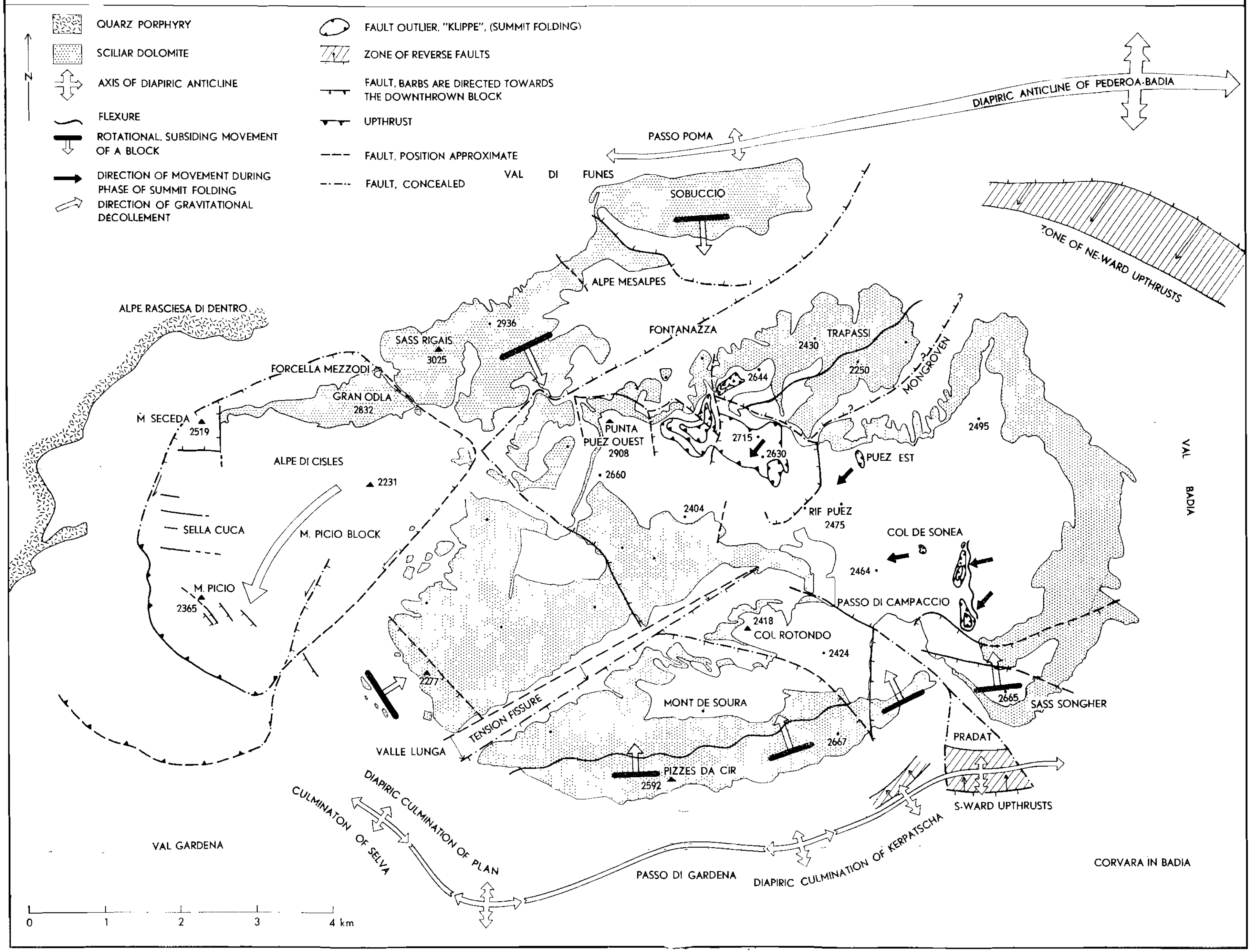



Fig. 51

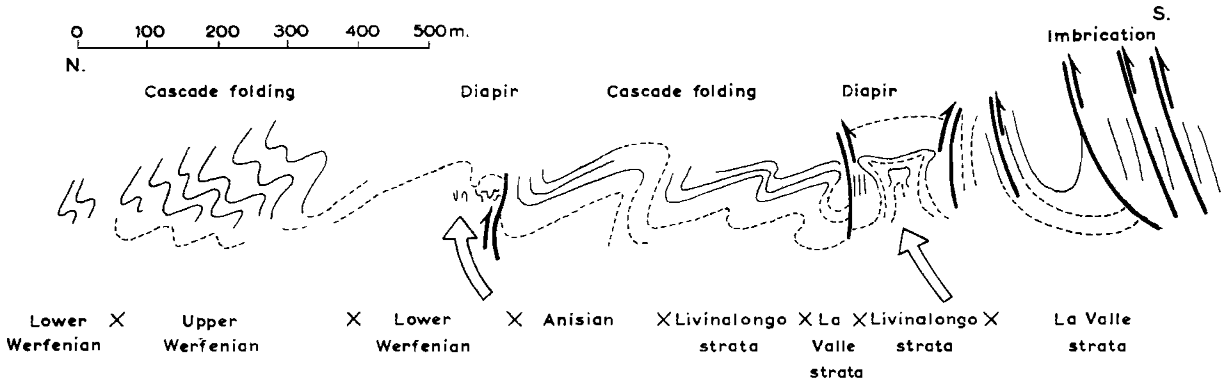



Fig. 30 Schematized section of the Triassic in the Badia Valley along the road between Pederoa and Badia. See for details the sections of the enclosed sheet III.

strata NE of Gardenaccia (our zone of NE vergent upthrusts). He thought that these sliding phenomena were the local, gravitational reactions to the tilting of the limbs of the N-S trending anticline of Badia. This badly exposed anticline should intersect the E-W trending anticline of Longiaru-Pederoa, and both are thought to be formed by alpine, tangential, compressive movements. These local, gravitative reactions — as they are correctly interpreted by Accordi — appear to fit better in the concept of a local, foundering mass-circuit; the denser reers acting as a hydraulic plunger (fig. 30).

The assumption of crossing alpine fold axes, the existence of which is contradicted by the field evidence, is thus made superfluous. Accordi pointed to the existence of a young system of vertical faults, which displaces parts of the thrust slices and their base. These faults show the influence of the additional load of the thrust masses on the top, which reinforced the still continuing subsidence and fracturing of the reef.

### The diapiric structures around the Puez-Gardenaccia-Odle group

These deformations are often related to an antithetic rotation of the edges of the group towards the diapirs. This caused flexures and normal faults parallel to the diapir folds around the reef mass.

The anticline of Passo Poma along the northern edge is the result of the combined plunger action of the Puez group and that of the Putia-M. Tullo group to the north of it. The latter was in turn influenced by the basement tectonics of the quartz phyllite block of Funes (see chapter VI, 2). The eastward extension of the Passo Poma anticline is the diapiric, anticlinal bulge of Longiaru-Pederoa. The Sobuccio block subsided towards the diapiric Passo Poma area, thereby tilting antithetically, so that it now dips 35° S. This block is bounded at its rear side by the arcuate system of normal faults, concave to the north, which extends from the Alpe Medalges to Pares.

The ridge with the summits Sass Rigais and Forchetta subsided to the NW and acquired an antithetic, inward dip of 25° to the SSE. The asymmetrical NW-SE valley of Fontanazza coincides with a normal fault at the rear side of this block.

The zone with steep upthrusts to the NE is the area of provenance of the gravity slides, which produced the "Klippen" of norian dolomites on the summits. More data about this zone are given in chapter VI, 4.

A good example of the relation between a subsided and tilted block and its frontal upthrusting is found at the SE corner of the Gardenaccia plateau. The diapiric anticline along the southern border of the group was strongly deformed and imbricated here by the subsidence of the Sass Songher block. It sank along two faults. The northeastern one runs from the Passo di Campaccio through the Val Sura north of the Sass Songher. The deepest exposure of the Puez-Gardenaccia group, where Sciliar dolomite crops out, is found just here, near the entrance of the Val Scura at less than 1600 m (Reithofer, 1928 a, p. 309).

The rotation and apparent underthrusting of the Sass Songher block is visible in the deformed Raibl strata below the summit (see fig. 32). The southern rim of the Puez-Gardenaccia group with the Pizzes da Cir (2592 m) and the Sass di Campaccio (2667 m) dips 26° NNE, slid southward and caused the diapiric anticline of the Passo di Gardena, which extends eastward and westward as the asymmetric, diapiric culminations of Kerpatscha (2064 m) and Plan (  m). In the elongate culmination of Kerpatscha the core consists of anisian dolomite (see fig. 33 and fig. 34) which has abnormal contacts with the enveloping ladinian volcanics. In the longitudinal section a small dome with a diameter of about 100 m illustrates the irregularity within the greater unit by the local protrusion of smaller parts.

The culmination of Plan has a triangular form, in its eroded core upper permian Bellerophon crops out. The form and position of this diapiric

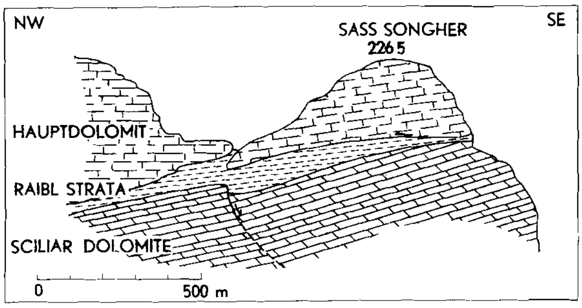



Fig. 32 Section of the Sass Songher at the SE side of the Puez-Gardenaccia-Odle group (After Groenewold, unedited). The dolomite block rotated backward by subsidence in its plastic base. The plastic Raibl strata are reduced by the sliding movement of the norian dolomites.

bulge between the reef groups of the Sella, the Puez-Gardenaccia-Odle and the Sasso Lungo indicate that its genesis was the result of the combined plunger action of these three groups. Although on a smaller scale this bulge has the same character as the domes of the Buffaure and the Campolongo, which are discussed in the chapters VII, 4 and VII, 5. Abnormal contacts between Werfenian and Ladinian volcanics in the southwest corner, the absence of the Livinalongo strata northeast of Piz Culaces and the fault, which only affects the mantle of the culmination east of Plan confirm the piercing character of the structure (see „Carta geologica della Val di Fassa", Leonardi, 1961).

The surrounding fringe of diapiric structures at the base of the Puez-Gardenaccia group has another culmination in the westward extension of the Passo di Gardena anticline at Selva. It can be traced still farther north-westward to the Alpe Suraga, where this belt of diapirs is cut off by the M. Picio slide (see chapter VI, 2 b, and fig. 31).

The Vallunga is a large, trough-shaped valley which extends into the heart of the group. Accordi (1955, p. 77) is of the opinion that the erosion was guided by a joint or unimportant fault. It is remarkable that the valley does not follow the structural SW-NE axis of the saucer-shaped basin but is found parallel to it in the northwestern limb, about 500 m NW of the axis.

We think that the valley is a glacially remodelled rift or tension fissure, which was opened by the southward gliding and subsidence of the southern border of the Puez-Gardenaccia group (the Pizzes da Cir and the Sass di Campaccio blocks, mentioned above).

Younger normal faults, divide the central Puez area into a number of blocks, such as the fault northeast of Col della Pieres (2759 m), the fault northeast of point 2915, where the northeastern block subsided about 125 m, and the fault separating the summit foldings of the Trapassi block from the Puez slides with a throw of about 200 m.

## The age of the movements

The oligocene erosion level was probably the topographic level over which glided the slices of the summit foldings on the top of the Puez-Gardenaccia-Odle group. The original oligocene level was lowered by post-oligocene erosion, which carried off the greatest part of the soft cretaceous and jurassic strata on the norian Hauptdolomit. The actual high plateaus of Puez and Gardenaccia are thus somewhat below the oligocene topography. The basal thrust plane under the slices of the summit foldings which limits the upper side of the Cretaceous and Jurassic in the isolated peaks, can be considered as the preserved oligocene topography.

The observation that these gravity slides covered the oligocene level of erosion indicates a post-oligocene, probably early miocene age of the summit foldings in the Puez-Gardenaccia-Odle group. The diapiric fringe must have come into existence, at least partly, in pre-pliocene time, since the southern anticlinal limb of the diapiric, anticlinal bulge of Plan was cut by the pliocene "Tre Passi level" of erosion at an altitude of 2100-2200 m. The flexures and faults within the reef mass belong to the same phase of deformations and, therefore, they will be also partly of pre-pliocene age.

However, the movements continue in the present time because of the re-activation of the field of potential energy by the progressive erosion in the surrounding valleys.

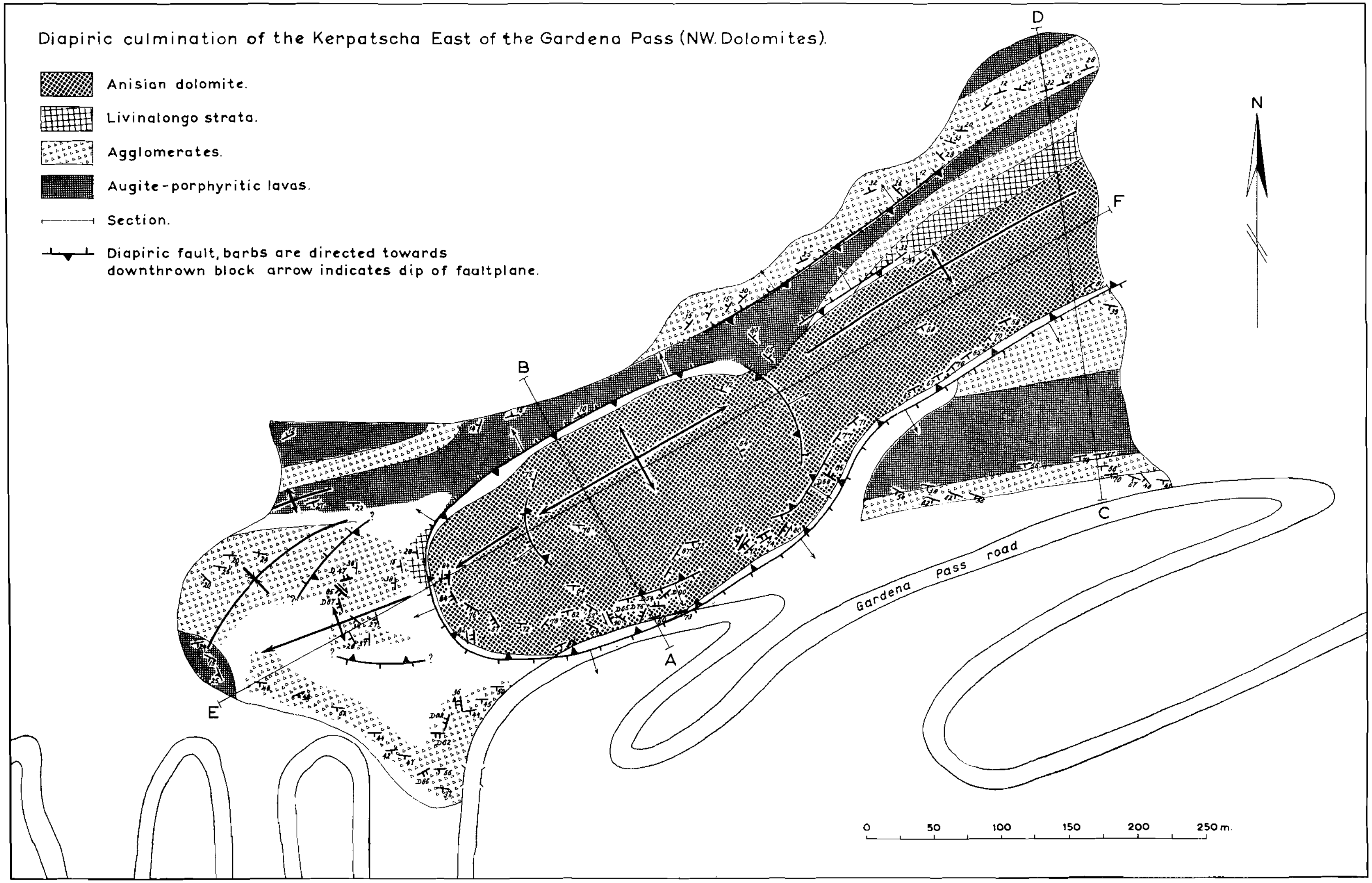
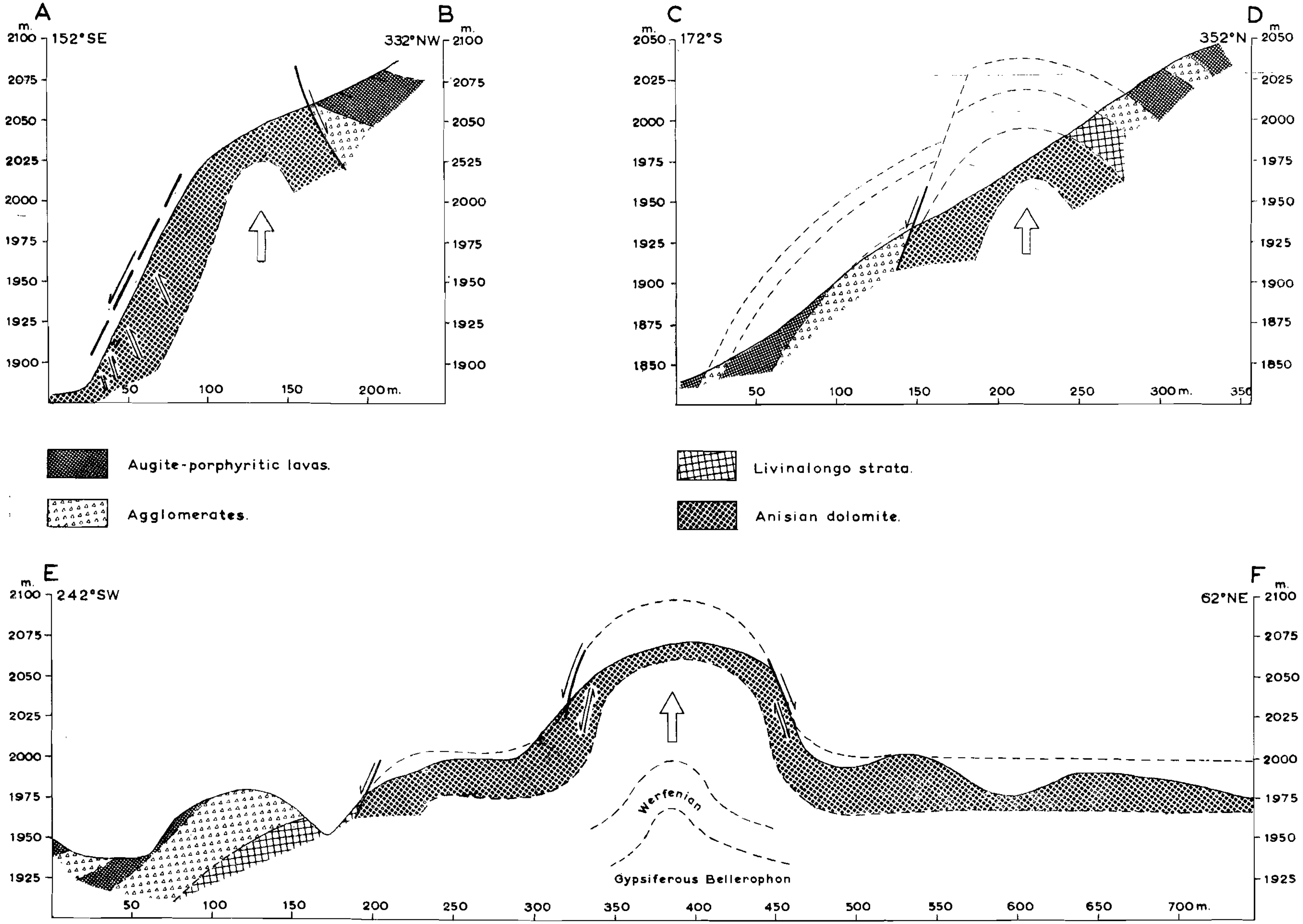



Fig. 33 After Groenewold (1961, unedited report Utrecht).




Longitudinal section of the Kerpatscha culmination (Passo di Gardena).

Fig. 34 After Groenewold (1961, unedited report, Utrecht).

## VII, 2. THE SELLA GROUP.

The Sella group is an almost circular mountain group with a diameter of 6 km, situated in the centre of the NW Dolomites. The highest summit of the group, the Piz Boè, rises to 3151 m. The isolated Sella mass is surrounded by deep valleys, connected by the wellknown series of four passes: the Passo di Gardena (2125 m) to the north, the Passo di Sella (2218 m) to the west, the Passo di Pordoi (2250 m) to the south, and the Passo di Campolongo (1875 m) to the east.

The lower part of the steep flanks of the Sella group consists of the massive, carnian to eo-raiblian Sciliar reef dolomite (300-600 m exposed), which is overlain by the Raibl strata (zero to 90 m). These Raibl strata are marly, dolomitic or clastic and are clearly distinguishable in the exterior parts of the reef, but near the centre they grade into stratified dolomites. There they are hardly distinct from the underlying Sciliar dolomite and the overlying Hauptdolomit (present thickness 200-300 m). The Raibl deposits form a marked structural terrace between the steep slopes of the Sciliar dolomite and the Hauptdolomit. Small relics of jurassic and cretaceous rocks are preserved on the top of the Hauptdolomit. Around the reef the heteropic sedimentary and volcanic deposits of middle triassic age are found in the facies of the La Valle and San Cassiano strata; NW and N of the Sella mass upper permian and lower triassic strata are exposed in the diapiric anticline of Gardena and the culmination of Plan, and to the SW of the Sella reef these older rocks crop out in the diapiric Col Rodella area (see chapter VII, 3).

The geology of the group is well known through the investigations of Mojsisovics (1879), Ogilvie Gordon (1899), Diener (1900), Furlani (1909), Reithofer (1928 a), Nangeroni (1938), Accordi (1955), Leonardi (1955), Leonardi and Rossi (1957), and Leonardi (map 1961). The most important of these publications are the monograph by Reithofer, the morphological study by Nangeroni, the detailed investigations of the summit thrusts by Accordi, and the study of the reef development and facies heteropy by Leonardi and Rossi.

The Sella group has a saucer-shaped structure, showing along the edges maximal inward dips of 10°. Extensive parts of the centre, however, have only dips of some degrees or the strata are horizontal. The eastside has no saucer shape, but sinks steplike to the east along a set of N-S striking normal faults (fig. 35).

At present the Sella mass is structurally the deepest part of the Fassa area. The tectonic history of the group is roughly the same as that of the Puez-Gardenaccia-Odle group, described in the preceding chapter (VII, I).

The undisturbed, horizontal sedimentary series — ranging from the upper permian Bellerophon to the lower cretaceous marls — was subjected to a stage of erosion of its upper part during the middle Cretaceous: a simultaneous deposition took place of breccias and conglomerates in depressions (see chapter III, I). A phase of general planation by erosion followed in the upper Oligocene (see chapter IV). The norian Hauptdolomit is truncated by this oligocene level, which was deformed later and is found now between 2750 and 2900 m above sealevel. This oligocene erosion surface gives the group its present plateaulike appearance. The Piz Boè is the sole culmination rising with steep flanks some hundreds of meters above this gently undulating erosion level.

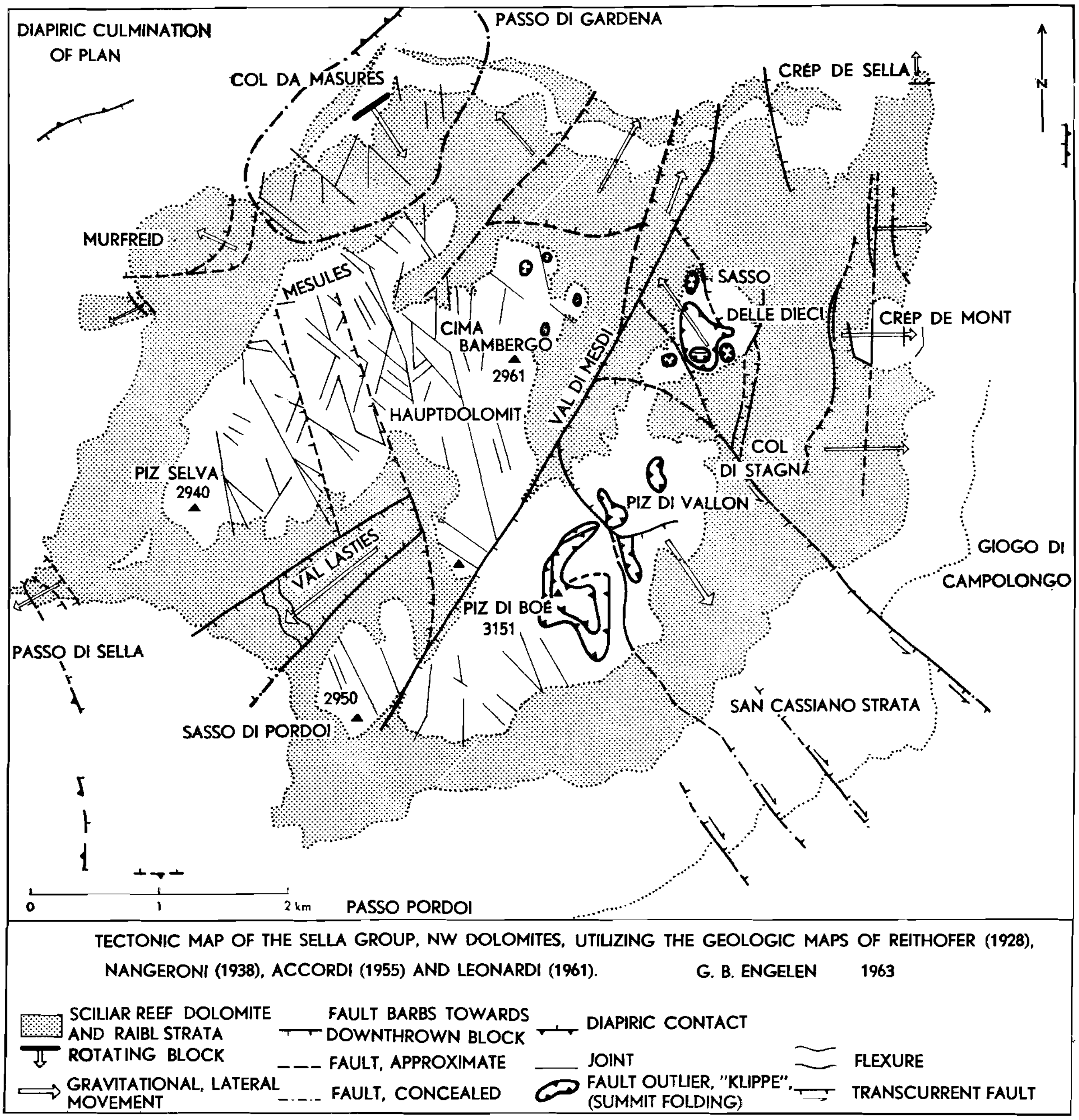
The subsidence of the Sella group into its plastic base and the related rising of diapiric domes along the circumference (the Campolongo dome to the east and the Marmolada bulge to the south) will have started already in the beginning of the Tertiary.

Sheets of norian Hauptdolomit and liassic limestones glided from the flanks of the Marmolada bulge domed up SSE of the group to the depressed centre of the Sella area. The sheets slid over the oligocene erosion level that had already developed in the lower parts of the landscape ("Reliefüberschiebung"); in this case the erosion surface was formed in the norian dolomites which covered the reef mass. Thus the intense dislocations in norian and liassic strata on the top of the only slightly deformed reef were formed.

These complications on the Sella group were elucidated by Accordi (1955). This author found that a large part of the group had once been covered by two extensive sheets of norian dolomites, which he calls the third and the fourth sheet. These sheets slid over the autochthonous Norian. On the Piz Boè another two overthrust sheets are distinguished by Accordi, both composed of liassic strata. They occur between the norian sheets and the undisturbed, autochthonous norian base. The liassic sheets are thinner than the Hauptdolomit thrust masses (20 m versus 50 and 80 m for the third and fourth sheets) and their areal distribution is restricted to the Piz Boè.

Basing his conclusions on the present distribution of the outcrops of the third and fourth sheet, Accordi supposes that these are relics of thrust sheets of Hauptdolomit which had originally a length and width of about 2 kilometer. However, if they originated by sliding movements, it is not necessary that they were originally formed as coherent overthrust sheets. From the outset they may have had the character of more or less isolated "Klippen" which slid from the tilted edges to the centre of the subsiding reef mass (the latter deformed during this subsidence to a saucer shape).

The fact that now the younger strata of the first and second unit underlie the older ones of the third and fourth unit is the common phenomenon of diverticulation caused by the succesive décollements of units sliding from a progressively rising




TECTONIC MAP OF THE SELLA GROUP, NW DOLOMITES, UTILIZING THE GEOLOGIC MAPS OF REITHOFER (1928), NANGERONI (1938), ACCORDI (1955) AND LEONARDI (1961). G. B. ENGELEN 1963

Fig. 35

and/or tilting column of sedimentary strata (see fig. 56 and Lugeon, 1943).
Accordi found a mean SE or ESE direction of provenance for the sliding from the orientation of the imbrication, the fold axes, the striae etc. He suggested the area of Soura Sass, about 5 kilometer southeast of the Piz Boè as the possible area of origin of the important third and fourth units.
The first and second unit he considers to be secondary upthrusts in front of the advancing, pushing third and fourth unit. The present difference in altitude between corresponding strata in the Soura Sass and Sella areas of 1000 m is quite sufficient for gravity sliding, but a provenance of a part of the thrust masses from the top of the nearby Campolongo dome to the east (which was eroded and col-

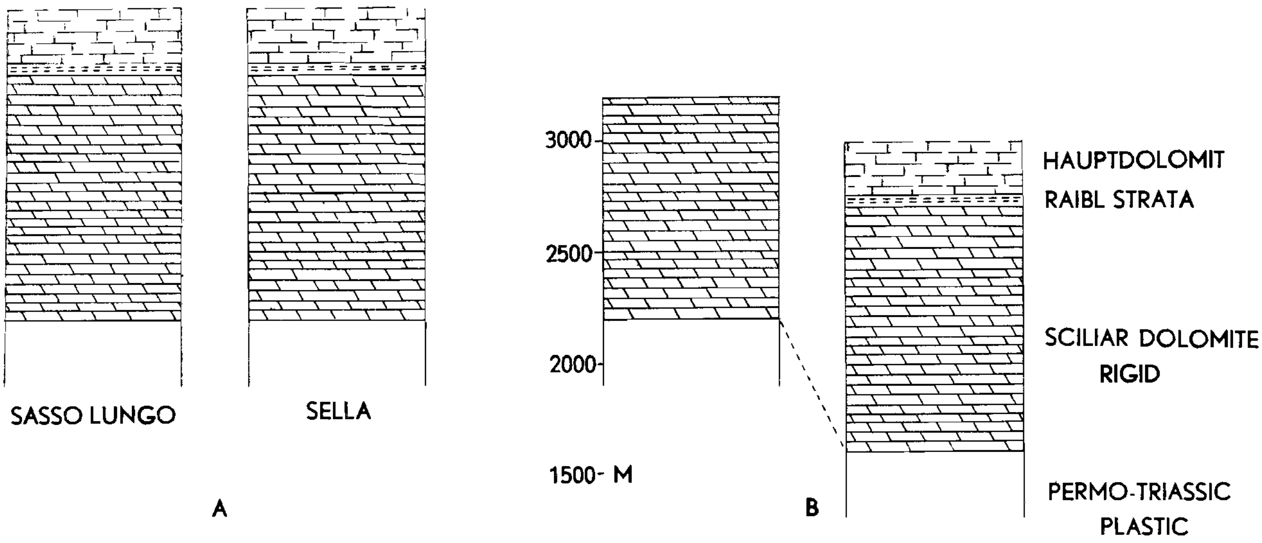



Fig. 36 Scheme of the differential subsidence of the adjacent Sasso Lungo and Sella groups. a) initial situation before subsidence b) present situation. The north side of the Sassa Lungo group and the east side of the Sella group were chosen for comparison.

lapsed later, see chapter VII, 5) is more probable. The measured direction of provenance S 65° E (Accordi, 1955, p. 121) for the third unit at the Cresta Strenta is in favour of this supposition.

We completely agree with Accordi on the gravitative character of the mentioned phenomena. Perhaps these thrust sheets should be considered rather as a part of the local mass circuit formed by the subsiding reef and the upbulging surroundings, than as the secondary gravitative reactions to the tilting of the limbs of regional folds, formed by a general tangential alpine compression.

On the average the whole Sella group tilted to the east during its subsidence; this is evident from the descent of the Raibl level from 2700 m at the west side to 2500 m along the southeastern edge of the group. The northeastern part subsided even more along a set of N- S faults, so that Raibl strata are now found there as low as 2080 m above sea-level.

The differential subsidence of the Sella group, compared with the Sasso Lungo group to the west, is demonstrated in fig. 36.

Leonardi and Rossi (1957) concluded from their investigations on the facies heteropy of the Sciliar dolomite that only the upper part of the reef is actually exposed and that the present exposed thickness of the Sciliar dolomite of 550 m must be doubled to obtain the real thickness of the reef mass. We think that this can be explained by the great subsidence of the Sella group as a whole. The volume of plastic matter, squeezed away by the subsidence of the Sella reef, can be estimated by multiplying its area of 36 sq. km by a mean subsidence of at least 0,5 km.

The sedimentary column of the Sella group has at its top about 18 cb. km less volume than the adjacent sedimentary column of the Sasso Lungo. This does not imply that the former subsided about half a kilometer together with its foundation (the quartz-phyllitic basement complex). It is much more probable in the light of the local geological circumstances and tectonic structures that the Sella reef acted as the heavy plunger of a hydraulic press, squeezing out the plastic lower part of the sedimentary column between the reef and the basement complex and pushing it up into the surrounding diapiric bulges. We have to do here with a local, mechanically and energetically coherent mass circuit (Van Bemmelen, 1958). It is not necessary to shift the problem of the loss of matter to unknown depths, using the deeper substratum as an "asylum" in the tectonic interpretation of the area (compare Van Bemmelen, 1963).

The largest part of the volume of 18 cb. km, which disappeared by subsidence was volumetrically compensated by the rise of the Marmolada bulge and the Campolongo dome, south and east of the Sella group. Smaller mass displacements were directed towards the Col Rodella area in the west and the Gardena area in the north. We may deduce from this local subsidence of at least 0,5 km that all (or the greatest part) of the underlying plastic Bellerophon and werfenian strata, which may have together a maximal thickness of 620 m. were squeezed out towards the surrounding diapiric bulges. No further subsidence of the Sella group of any importance is to be expected.

The La Valle and San Cassiano strata around the reef were easily removed by erosion as soon as the protective cover of Hauptdolomit over the rising bulges had disappeared by tectonic denudation (the above mentioned décollements, which gave rise to the Sella summit thrusts) and by normal erosion attacking the emerging bulges. This accelerated denudation and erosion started a process of relief inversion. The much more resistant reef became a high, isolated mass, surrounded by deeply eroded valleys.

The erosion around the Sella group from late oligocene to pliocene time can be subdivided in some minor stages with intervening periods of erosional planation (Nangeroni, 1938, p. 20). The next general planation in the Dolomites after that of the Oligocene is the pliocene level of about 2100 m, the "Tre Passi" system (see chapter IV).

The subsidence of the rigid reef mass was accompanied by a distension and breaking into a number of blocks. These blocks tended to subside and to move radially away to the surrounding valley floors. The relief inversion had created a field of potential energy, with steep gradients directed from the flanks of the reef mass towards the valleys. The combined movements of sinking and lateral spreading are indicated in the tectonic map of the Sella group for the individual blocks by open arrows (fig. 35).

The east side of the group with its step-faulting is the edge of the saucer, which broke down in a younger stage. A NE-SW striking fault through the Val de Mesdi separates the broken eastern part from the less disturbed western part of the saucer. The fault bifurcates at the NE end. A throw of 20 m was measured in the SW (Reithofer, 1928, p. 563). The importance of the steplike subsidence of the east side along a series of N-S running faults, causing a horst-and-graben structure of narrow slices, can be measured by comparing the altitude of the Raibl strata at about 2680 m near the Cima Bamberga in the centre of the group with their altitude of 2080 m three km farther east along the margin (see Reithofer, 1928, profile 2). This difference shows a subsidence from west to east of 600 m over a horizontal distance of 3000 m.

The Val Lasties in the SW border of the Sella group is a rectangular tectonic valley, formed by the subsidence of a slice of Sciliar dolomite with an area of about 0,5 x 1,75 sq. km. The relative, vertical subsidence is 200 m near Pian de Roche in the NE part of the valley, and 400 m at the entrance near Sora Cogoi (fig. 37). The throw can be measured by the differences in altitude of the Raibl strata, cropping out in the steep walls of the valley and exposed on its bottom. The total amount of plastic matter which flowed away from the base of this block to the adjacent Col Rodella diapirs can thus be estimated at 0,5 x 1,75 x 0,3 = 2,62 cb.

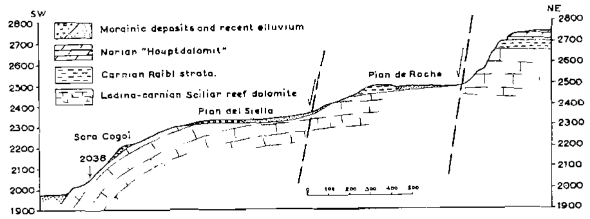



Fig. 37 Section of the rectangular, tectonic valley at the SW-side of the Sella group (Val Lasties), modified after Reithofer (1928, p. 564).

km. Three small, hanging valleys at the end of the Val Lasties are cut off by the faults around the Val Lasties block. The subsidence of the block is probably of late pliocene or pleistocene age because it seems to be related to the incision of the Fassa Valley and the simultaneous diapirism in the Col Rodella area.

An example of subsidence of a block with simultaneous rotation towards the adjacent diapiric area is presented by the NW corner of the group. An oval-shaped block subsided outward along a curved fault plane and during this sliding movement it rotated 5° - 10° inward. The underlying plastic matter was squeezed to the NW and was pressed upward, which caused the steep, diapiric contact within the San Cassiano formation in front of the block at the Passo di Gardena (fig. 38). The southeastward tilt of the subsided block is indicated by the tilt of the base of the wedge of San Cassiano strata (interfingering with the reef), which was originally a horizontal plane. An elongate, depressed zone was formed in the rear of the rotating slide block, at the base of the undisturbed scarp of the Mesules (fig. 39). That zone has now a small endoreic drainage system and the depressed zone was partly filled by an elongate glacier with its moraines along the base of the Mesules scarp. The small glacier vanished in the last few decades conform the tendency to a general retreat of the glaciers in the Alps (see for similar structures in

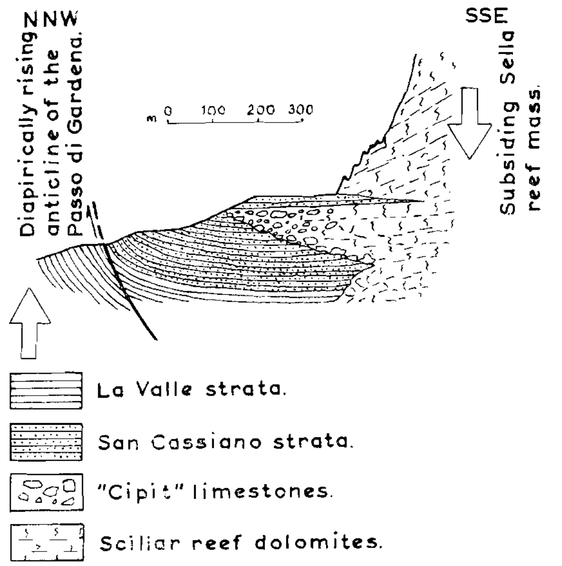



Fig. 38 Section at the Passo di Gardena with the facies heteropy of the volcano-clastic San Cassiano strata and the Sciliar reef dolomite of the Sella group, modified after Leonardi and Rossi (1957, Tav. II).

the volcanic Sunda complex of Java: Van Bemmelen, 1949, plate 32).

The southeastern part of the Sella group shows the outward movement of a block (Piz de Vallon) on the top of which lie some relics of the thrust sheets between the Piz Boè and the Sasso delle Dieci. Reithofer (1928, p. 561-562) observed a series of NW-SE dislocations in the San Cassiano strata between the Sella group and Arabba in the upper Cordevole Valley, southeast of it. These occur just in front of the Piz de Vallon block. The block is limited to the NE by a straight left-lateral wrench fault (see Reithofer, 1928, p. 567), to the NW by an arcuate fault which partly coincides with the Val de Mesdi fault, and to the SW by the right-lateral wrench fault along the eastern base of the Piz Boè (see Accordi, 1955). There is an obvious mechanical relation between the subsidence of the Piz de Vallon block and the southeastward protruded (diapiric) mass of San Cassiano strata in front of it. The latter is the volumetric compensation for the mass displacements of the mobile matter squeezed out from beneath the block.

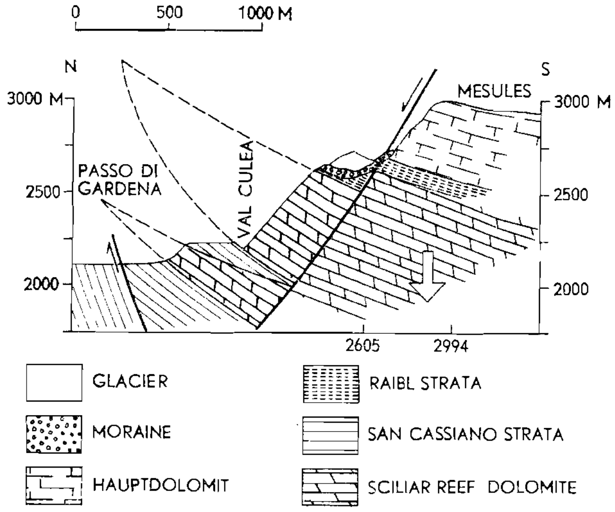



Fig. 39 Schematic section of the Mesules at the NW side of the Sella group with rotational block movement along the border of the reef mass.

The isolated, local pillars or "towers" of dolomite along the border of the reef such as the Piz Chiavazzes at its SW side are minor examples of the tendency to lateral spreading, comparable to Ampferer's (1929), concept of "Gebirgszerreissung". Such "towers" may be seperated from the main mass by joints without differential vertical movements (Torri di Sella, Piz Chiavazzes, Piccola Pordoi), or they subsided along faults while sliding sidewards (Torri di Murfreid, Crep de Sella).

## VII, 3. THE SASSO LUNGO GROUP AND THE DIAPIRIC AREA OF THE COL RODELLA.

The Sasso Lungo group and the Col Rodella area, situated in the nortwestern Dolomites between the Gardena and Fassa Valleys, have been studied by many: e.g. Richthofen (1860), Mojsisovics (1879), Weller (1920), Ampferer (1929), Von Klebelsberg (1935), Mutschlechner (1935), Heissel and Ladurner (1936), Ogilvie Gordon and Pia (1940) and Leonardi (1941, 1943, 1955, 1961).

The northwest- and northward directed upthrusts along the base of the Sasso Lungo reef, and the very complicated deformations in the Col Rodella

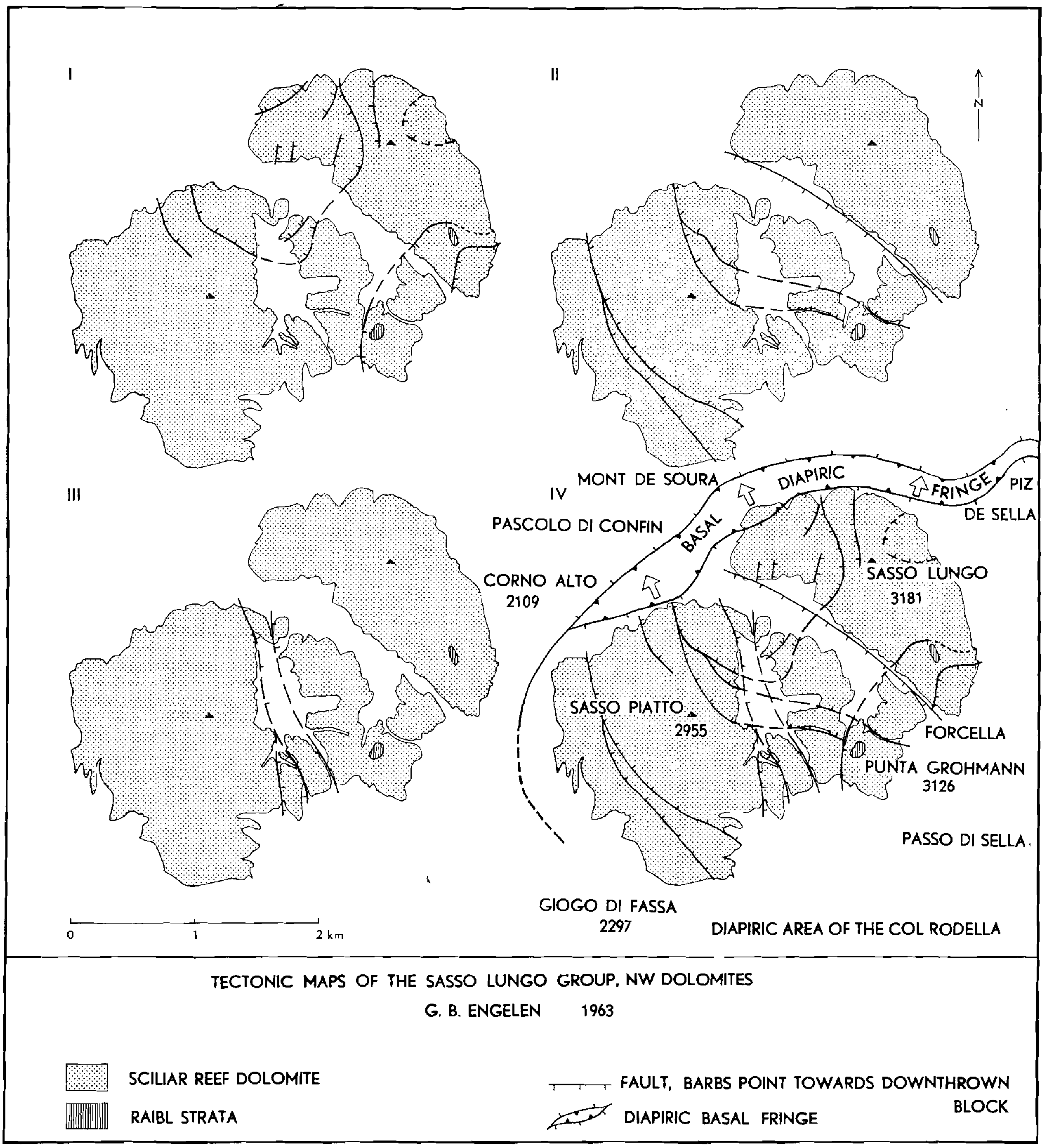



Fig. 40

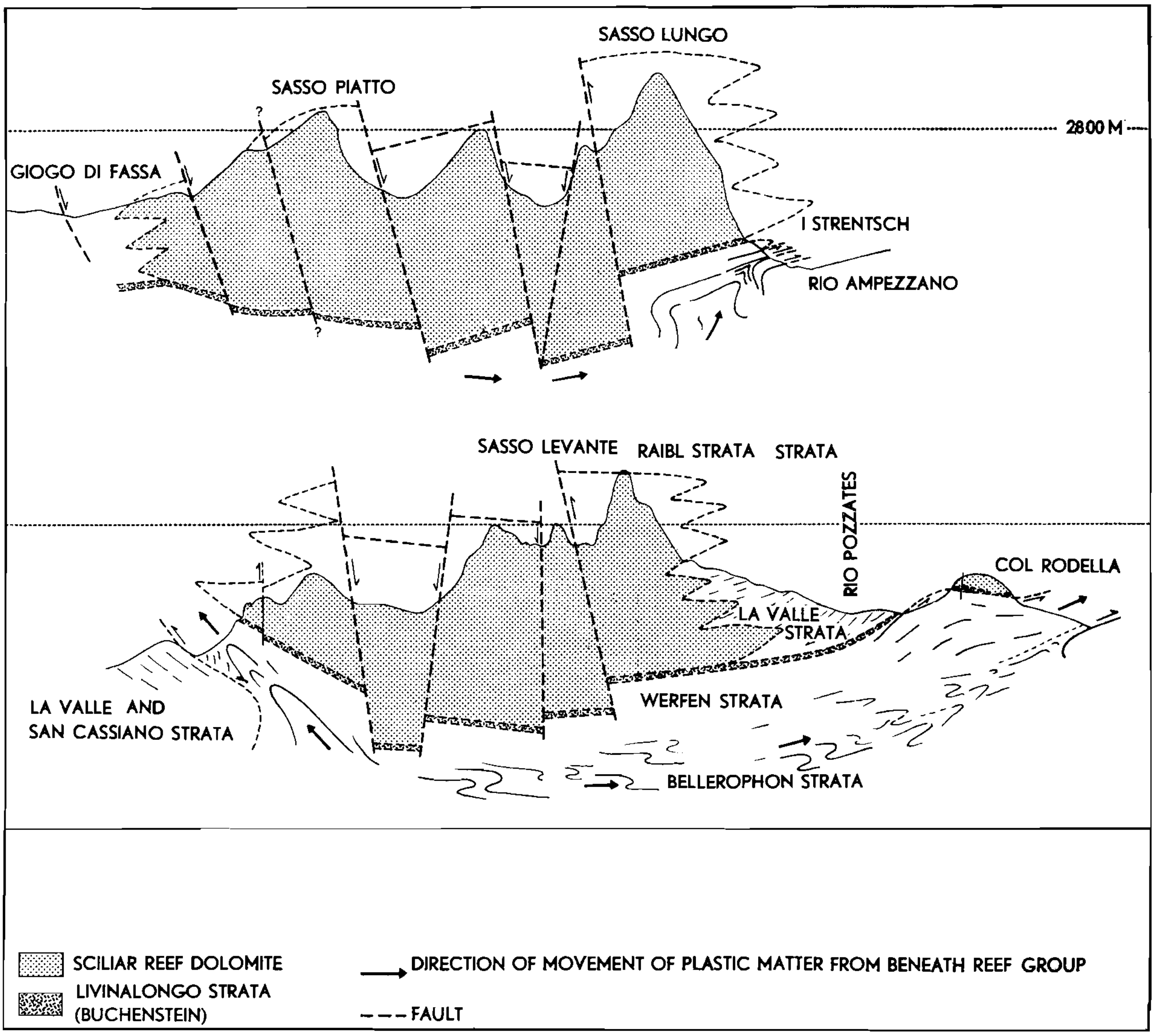



Fig. 41

area seemed to defy a simple mechanical explanation. The swift variation in direction of movement over short distances could not be satisfactorily accounted for by a simple regional pattern of tangential, compressive stresses during the alpine orogenesis. On the other hand, the tectonics of the Sasso Lungo group and its surroundings can easily be elucidated if the concepts of gravity tectonics are applied. A logical relation can then be established between the fault pattern within the reef mass, the facies heteropy, the erosional history of the area, and the deformations in the adjacent plastic Permo-Triassic.

Leonardi's "Carta geologica della Val di Fassa" (1961) presents an accurate, recent map of the Col Rodella area, southeast of the Sasso Lungo group. As a base map for the Sasso Lungo group, however, Mutschlechner's map (1931) was used, because it gives a much better representation of the topography of the group.

The ladino-carnian Sasso Lungo reef complex is a good example of the disintegration of a reef into blocks and the simultaneous subsidence of these blocks into their mobile foundation of Permo-Triassic because of their own weight.

The following processes and resulting structures can be distinguished:

The soft La Valle and San Cassino strata were easily removed by erosion around the reef. This occurred in mio-pliocene time down to the pliocene erosion level at 2100-2200 m (the "Tre Passi" system). Thus the counteracting weight in the hydraulic plunger system was reduced and an unstable situation was created. The reef began to subside into the plastic werfenian shales and gypsiferous Bellerophon strata underneath. These underlying sediments were squeezed away radially, which resulted in the formation of three types of tectonic reactions:

### a) The basal diapiric fringe

A fringe of Werfenian and Anisian between the reef and the volcanic series around it crops out along the base of the Sasso Lungo group at the NW and N side between the Corno Alto and the Piz de sella (see fig. 40).
Already Ogilvie Gordon and Pia (1940, p. 110) supposed a relation between the location of this disturbed zone and the facies transition between reef and volcano-clastics. This tendency for diapiric structures to be formed in belts of sudden changes of the weight of the overburden — as can be observed here in nature — was also found in experiments by Ramberg (1963, p. 30).

The imbricated core of the diapir was folded and thrust more or less horizontally over the La Valle strata in a centrifugal direction (see profile of fig. 41). The direction of the movements is normal to the reef edge: to the north along the northern border, and northwestward between the Corno Alto and the Mont de Soura. The diapir changes into a northward upthrust at the Piz de sella and it disappears farther east. A continuation of the dislocation near the Corno Alto (the SW extremity of our diapiric fringe) into the NW-SE striking fault over the Giogo di Fassa was suggested by Ogilvie Gordon and Pia (1940, p. 33), but this possibility cannot be verified in the field on account of insufficient exposures.

### b) Horizontal movements toward the surrounding valley floors

The "outlet" in the diapiric fringe and the great distance from the reef mass to the Gardena Valley caused only a small portion of the Permo-Triassic to be squeezed in northern directions, that is to the diapiric culmination of Plan, 3 km NE of the Sasso Lungo (see fig. 31 and chapter VII, 1). A very small diapir (cross section about 50 m) pierces the volcanic strata in a point situated 1250 m SSW of Selva (Wolkenstein), near Fratacces (see Mutschlechner's map). The bulk of the mobile foundation of the reef was squeezed southward to the Col Rodella area in the Fassa Valley. This process occurred from late-pliocene to recent time, and is discussed separately in the next subchapter.

### c) The disintegration of the reef into blocks

The squeezing out of the underlying plastic, upper-permian and lower-triassic strata has not been a perfectly uniform process, and neither is the reef itself a homogeneous and isotropic mass. Consequently, torsional deformations within the dolomite mass occurred and the reef broke into a number of blocks. These blocks could now settle differentially.

We made a tectonic sketch map with the main faults and tectonic blocks (fig. 40). This map is based on the evidence presented by:

1) the occurrence and direction of steep gorges, transsecting the reefbody,
2) the differences in altitude of the base of the Raibl deposits,
3) brecciated zones and striae,
4) the morphological aspect of the broken topography of the group,
5) the interrelations between subsided blocks and upthrusts at their base.

In the fault pattern a subdivision in two types of faults appears.
a) Arcuate, saucer-shaped fault planes envelop blocks along the edges of the reef, where free space for centrifugal movements was furnished by the erosional removal of the volcanic deposits around the group. The blocks slid outward and subsided. Such a subsided block lies at the southeast side of the group. On the higher parts of this subsided block (on the Sasso Levante, 3126 m, and the Langkofeleck, 3069 m) relics of the capping Raibl strata are found. Because of their lower altitude these Raibl deposits were less exposed to erosion than those of the neighbouring blocks, and so they could be preserved; whereas all Raibl strata were removed from the top of the other reef blocks of the Sasso Lungo group.
We may safely assume that the surface on which the Raibl strata were deposited was a horizontal plane, as it still is in the Sella group to the east. Differences in the present altitude of its occurrence must have been caused by differential vertical movements (in this case different rates of subsidence). On the Sasso Levante this base is situated at 3085 m. The summit of the Sasso Lungo with its altitude of 3181 m consists of the ladino-carnian reef dolomite, so that the Raibl strata were situated at a still higher elevation. The difference of about 100 m must be due to differential vertical movements within the Sasso Lungo complex.

## THE COL RODELLA AREA

The complicated minor deformations of the Col Rodella area will not be treated here in detail. For these data we refer to the existing publications and maps. We used the good, recent map of Leonardi (1961) as the basis for the interpretation of the tectonics of the Col Rodella area. It appears that a logical pattern of extrusion of the Permo-Triassic towards the "void" of the Fassa and Duron Valleys can be obtained by a re-evalution of the direction of thrusting along some of the faults in Leonardi's map (fig. 42).

All faults along the upper side of what we consider to be diapiric lenses — e.g. the fault along the base of the Col Rodella reef — were interpreted on Leonardi's map as upthrusts. This was a necessary consistency if one adheres to the idea of tangential compression; for in that case the lower block is considered to be the fixed one. In reality, however, the diagnostic observations indicate that the mass under the fault plane was pushed diapirically forward: this implies that we deal with a flatlying, normal diapiric contact. Also Ogilvie Gordon and Pia (1940, p. 73) tried to unravel the tectonics of the Col Rodella area by means of regional compression, but their description of the zone of Bellerophon, Werfenian and Anisian below the Col Rodella reef was already the unintentional description of a diapir: "Immer aber erscheint das Ganze wie eine fremde, von zwei Schubflächen begrenzte Masse. Denkt man sich sie weg, so ergibt sich zufällig eine fast normale Schichtfolge, da die Buchensteiner Schichten über der oberen Schubfläche auf den Sarldolomit unter der unteren zu liegen kämen".

Four diapiric zones can be distinguished. These zones were squeezed out successively as units parallel to the incised Fassa- and Duron Valleys. Their outcrops are more or less lense-shaped diapiric windows. Bellerophon, Werfenian and Anisian crop out in these windows, together or separately, depending upon the degree of horizontal movement within and the accidental, actual erosional exposure of the windows. The movements of the mobile matter to the "outlet" in the valley sides are rather irregular, which is typical for diapirism, because it is the result of the interaction between the fields

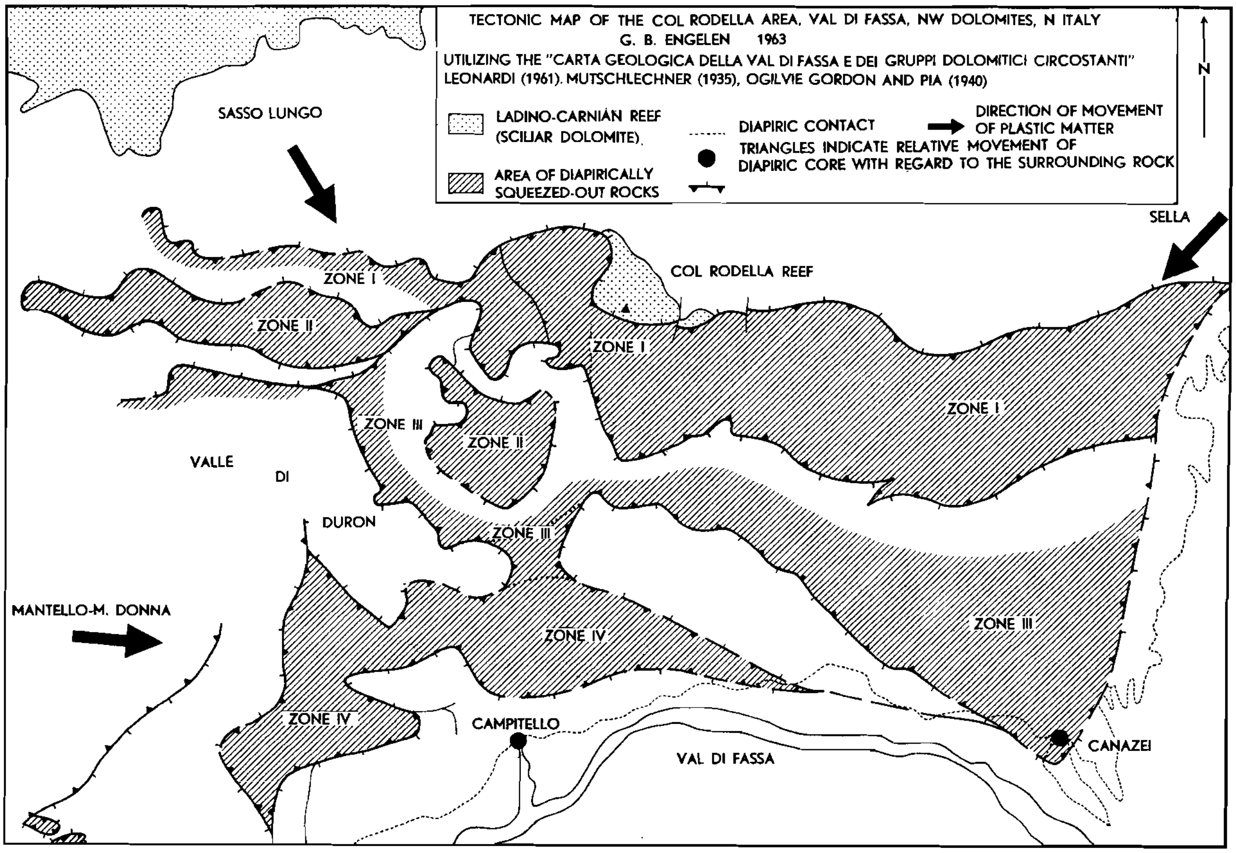



Fig. 42

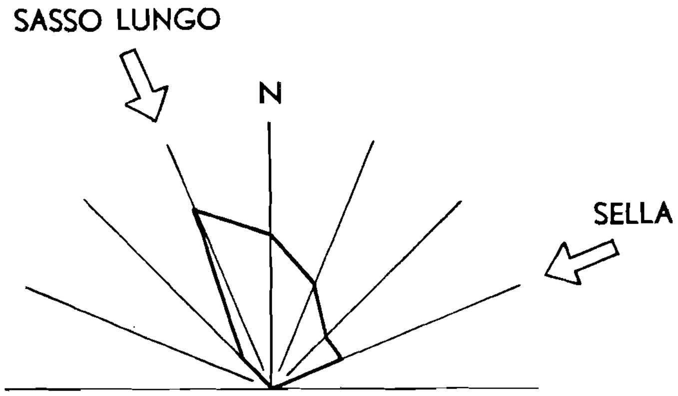



Fig. 43 Tectonogram with representation of movement features in the area of the thrust plane below the Col Rodella reef, after Ogilvie Gordon and Pia (1940, fig. 81). Each observed feature is covered by ½ cm in the diagram. The influences of the subsidence with related diapirism of the Sassa Lungo and Sella reef masses are visible, see also fig. 42.

of potential energy and the plasticity of the strata.

An example of these differential movements in the horizontal plane, in the direction of flow, is the circular diapiric window of zone II. Probably zone II had at first a lenticular shape; but its eastern part later started to move swifter forward than its surroundings and a mass with circular cross section was extruded. The case is geometrically comparable with salt dome tectonics in NW Germany, where locally saltstocks rise from elongate swells of salt (Trusheim, 1960). To obtain similarity a rotation of 90° is necessary, because diapirism in the Col Rodella area has a horizontal direction toward the valley floors in contrast to the upward, vertical direction in the sedimentary basin of NW Germany.

The diapirism in the zones I, II and III was caused by the combined plunger action of the Sasso Lungo and Sella groups. Ogilvie Gordon and Pia (1940, p. 81) published a tectonogram of the area east of the Col Rodella, which is reproduced in our figure 43. We interpret the dominant NNW-SSE direction in it as the reflection of the diapiric movements away from the Sasso Lungo group. The smaller ENE-WSW component illustrates the influence of the Sella group.

The position of zone IV shows that there the influence of the subsiding Sasso Lungo and Mantello-M. Donna group predominated. The subsidence of the Catinaccio-Mantello group, SW of the Col Rodella area, follows from the difference in altitude of 550 m of the top of the Werfenian on either side of the 7 km broad group.

The vertical and "en échelon" arrangement of the diapirs is probably related to the successive stages in the erosion of the Fassa Valley. Zone I will be the oldest, zone IV the youngest. The relation between the extrusion of a zone and a corresponding old valley floor is not so obvious here as in the sides of the Campolongo and Buffaure domes (see chapters VII, 5 and VII, 4). The diapirism was a more continuous process in the Col Rodella area because the "hydraulic pressure", exerted by the combined effects of the surrounding reef masses, was much greater than the stress field of the domes of Buffaure and Campolongo, which collapsed as a result of their own weight.

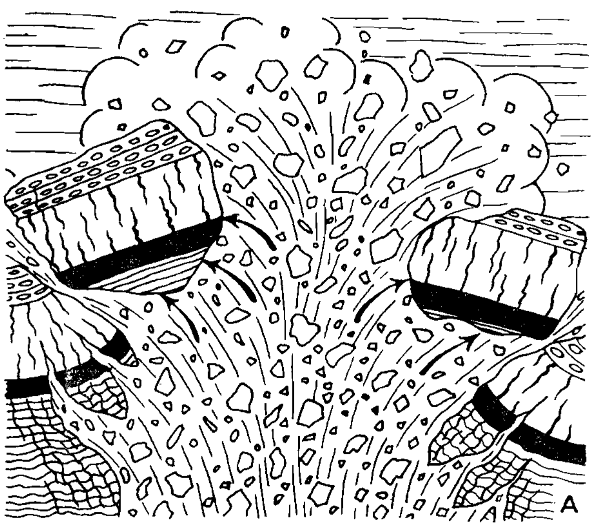
The disturbed situation at the eastside of zone III might be the result of triassic volcano-tectonics, as was suggested by Leonardi. But even if a part of the dislocations in that corner of the Col Rodella is of volcano-tectonic origin, yet later on this zone was also affected by the late pliocene and pleistocene diapiric movements.

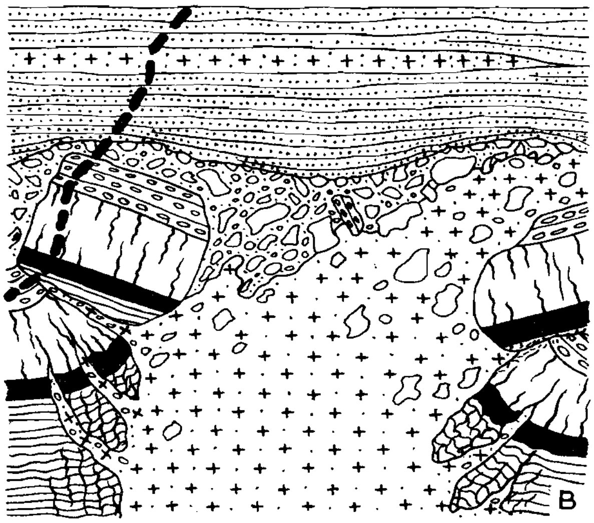
The diapirism of the Col Rodella area was only possible by the erosional carving of the Fassa Valley, which lies below the pliocene erosion level of 2100-2200 m. Thus the deformations have a late-pliocene and younger age.

## VII, 4. THE BUFFAURE DOME STRUCTURE.

The Buffaure is a mountain group with a NW-SE diameter of about 7½ km and a NW-SE diameter of about 5 km. It is bounded by the Avisio Valley to the north and west, the Val S. Nicolò to the south and the Marmolada mountain group to the east.
The middle-triassic (ladinian) volcanic series, consisting of tuffs, lavas and agglomerates, are exposed in the summit area of the group. These strata are almost undisturbed, showing only slight dips. However, strongly deformed lower-triassic skythian and anisian) rocks are found in discontinuous outcrops along the steep valley sides, around the summit area of the Buffaure.

Ogilvie Gordon (1927) interpreted the folds and faults of the Buffaure group as a complicated system of "torsion structures".
Leonardi (1953, 1955) suggested another explanation for this greatly disturbed fringe of lower-triassic around the undisturbed summit area of middle-triassic volcanic strata, he explained this situation as the effect of the violent expansion of the volcanic gases of an eruption of basic to intermediary magma in the core of the Buffaure group. It should have provided lateral, centrifugal forces, which pushed sedimentary units outwards. Upon these disturbed series the tuffs and lavas of the Middle-Triassic (Upper Ladinian, San Cassiano) could now be deposited without further complications (fig. 44).
Leonardi cites Hummel's publication on the genesis of the ladinian agglomerates as a proof for the possibility of such "vulcano-tectonic" phenomena. However, we found in Hummel's work (1932, p. 60) quite another statement, for: concluding his study on the origin of the agglomerates, he says that these volcanic breccias were formed **without** important explosions. The sedimentary, calcareous layers were broken by the movements of the lava, so that a mixture was formed which behaved as a lava, intruding in sills, or flowing out in sheets.



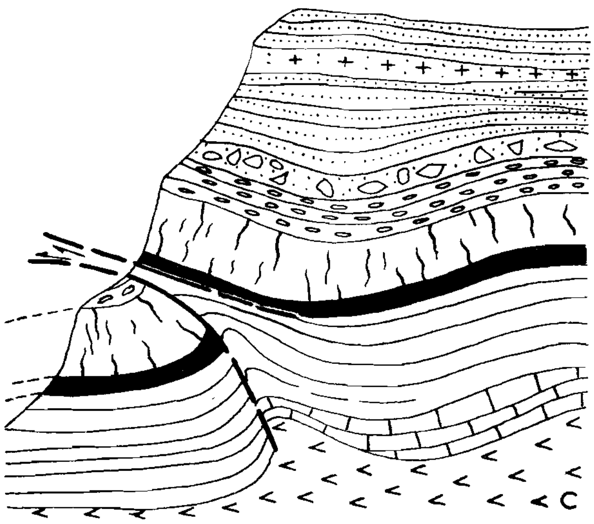
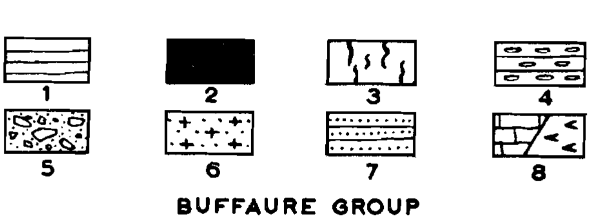
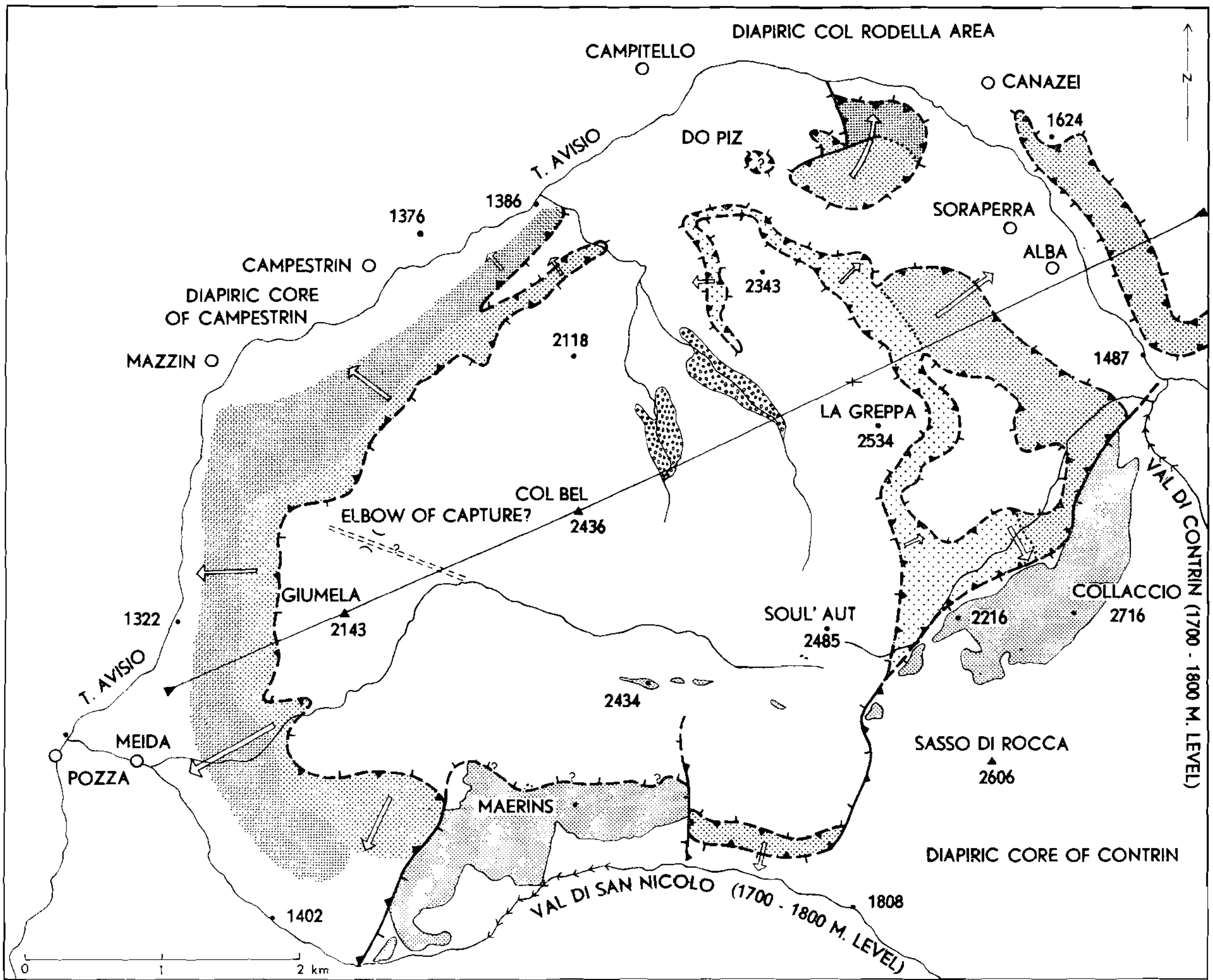




Fig. 44 A comparison of Leonardi's hypothesis (1955, a, fig. 5) for the tectonics of the Buffaure area (triassic volcano-tectonics with the interpretation by means of cenozoic lateral diapirism.
1. Werfenian 2. lower Anisian 3. upper Anisian 4. Livinalongo strata 5. agglomerates 6. augite-porphyritic lavas 7. ladino-carnian tuffites 8. Bellerophon limestones and gypsum.






TECTONIC MAP OF THE BUFFAURE GROUP, NW DOLOMITES, N ITALY
BY G. B. ENGELEN UTILIZING THE GEOLOGIC MAP OF LEONARDI (1961).

MARMOLADA LIMESTONE — YOUNGEST PLIOCENE DIAPIRISM AT 2000 - 2200 M — PLEISTOCENE AND RECENT DIAPIRISM ALONG THE ACTUAL VALLEY FLOOR — DIRECTION OF DIAPIRISM — SECTION

UPPER PLIOCENE TERRACE DEPOSITS — DIAPIRISM AT ± 1800 M — DIAPIRIC CONTACT

Fig. 45

The sedimentary fragments in the agglomerates are predominantly small (some cubic decimeters) but locally blocks of some cubic meters occur.
Leonardi draws an analogy between these agglomerates described by Hummel, and the chaos of enormous sedimentary blocks which measure in some cases thousands of cubic meters. The latter are found in the zone beneath the agglomerates. Since Hummel demonstrated that the relatively fine-textured agglomerates were formed without explosions, it is highly improbable that the huge sedimentary units were pushed radially outward by the expanding volcanic gases. The ladinian volcanism in this area was not accompanied by great explosions. The magmas were hot, basic, and had a low viscosity, and their ascent is characterized even by the absence of important explosive phenomena. Another curious fact, which is not sufficiently accounted for by Leonardi's volcano-tectonic hypothesis, is: in general, the relative stratigraphic po-

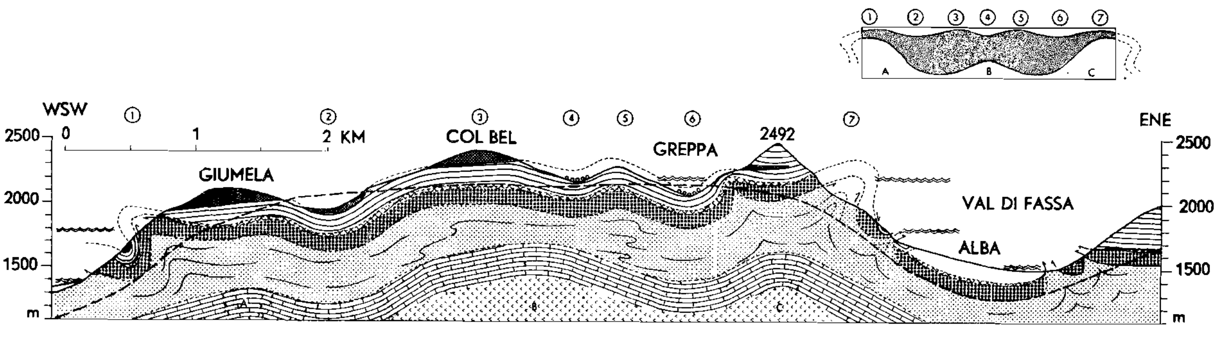



Fig. 46 Section of the Buffaure dome The small figure in the right corner is the pattern of settlement of a model dam on gelatin (Krynine, 1947, fig. 9:27), the extreme parts have been added. Dashed line indicates the base of the Anisian if no collapse had occurred. See for legend the enclosed sheet I.

sition between the sedimentary blocks has been preserved. On closer analysis, the sedimentary blocks appear to occur in zones at various levels in the volcanic series. This observation would require the assumption of at least several stages of violent explosions instead of one only.

These arguements make it difficult to unravel the structure of the Buffaure group as the result of triassic volcano-tectonics.

The following concept: young neozoïc gravity tectonics, seems to provide a closer fit with the field data.

The Buffaure area represents a large, flat dome in the ladinian volcanic series with a core of Bellerophon and Werfenian. This dome bulged up in the area between the subsiding reef masses around it: the Sella, the Sasso Lungo, the Catinaccio and the western part of the Marmolada. In the first stages of its formation the core grew by accumulation of plastic permo-triassic rocks, which were squeezed away from beneath the adjacent reef groups. A large "rim-syncline" formed around the dome, which determined the annular drainage pattern of the Avisio and the Rio di S. Nicolò, (fig. 45).

The formation of the dome can be dated as post-oligocene and pre-pliocene. Before the Oligocene the cover of norian Hauptdolomit above the ladinian volcanic series was still intact and prevented important vertical movements. During the violent erosion in the Miocene great parts of the easily erosible strata between the reef groups were removed, and only then could the hydraulic plunger action of the surrounding heavy reef blocks start. The upper limit of the age of the dome formation is the occurrence of alluvial deposits at 2050-2150 m west of the Greppa (2534 m), deposited by a river system which corresponds with the pliocene erosion level of 2000-2200 m (see IV, 1).

The Buffaure dome began to collapse as soon as the pliocene and quaternary erosion afforded outlets for the more plastic strata in the core through the sides of the incised valleys by means of horizontal diapiric movements. The theoretical form of the dome, indicated by the dashed boundary line between the Werfenian and the Anisian in the profile of fig. 46, was probably never realized, because its collapse started already during its growth. During the subsequent stages of incision of the Avisio and S. Nicolò rivers diapiric zones were extruded at successively lower levels; these levels correspond with old valley bottoms, which indicate interruptions in the vertical erosion of the rivers.

When the rivers started to carve their valleys in the rim-syncline the Buffaure dome became an isolated, collapsing structure. The plunger action of the reefs continued, however, and the plastic strata at their base now found an outlet in the valley sides opposite to the Buffaure group. So that at present we find there the diapiric areas of Campestrin, Col Rodella-Campitello and along the north side of the Avisio Valley between Canazei and Penia. This concept explains also the converging movements on either side of the Fassa Valley (see section, fig. 46).

The highest zone with centrifugal diapirism curves around the ridge la Greppa. It can be related with the erosion level of the rivers of the pliocene "Tre Passi level" of 2000 - 2250 m. The alluvial deposits between la Greppa and Col Bel are relics of this stage. The altitude of the diapiric zone diminishes from 2250 m east of la Greppa to about 2000 - 2100 m near Col Pelos. This northward tilt of the highest, disturbed zone is the effect of the subsidence of the northern corner by the younger diapir SW of Canazei.

The next extruded zone is more developed along the edges of the Buffaure dome, and it forms an almost continuous ring at an altitude of 1730 - 1800 m. It can be correlated with the youngest pliocene valley floors at 1750-1850 m, which are still found in the tributary valleys of the Avisio, e.g. the valleys of Contrin and the upper course of the valley of S. Nicolò (see also chapter IV, 1).

The quaternary diapiric zone coincides with the level of the actual valley floors where diapiric extrusion, folding and faulting probably has proceeded up to the present day. In many places the youngest pliocene and early quaternary zones cannot be seperated exactly because they merge into one another. Transitions also occur locally between the late-pliocene and quaternary zones.

A diapiric zone shows an alternation of more and less extruded parts, this causes the extremely irregular outcrop pattern of the lower triassic (skythian and anisian) rocks. The structural pattern of a similar, horizontally protruding, diapiric unit is given in fig. 48. This scheme is based on a smaller, better surveyable protrusion in the Cordevole Valley.

The collapse of the Buffaure dome is about symmetrical along a NW dipping axis from Soul'Aut to Campitello. The centre subsided along this axis, the northwestern corner sank most deeply. The underlying plastic rocks were squeezed diapirically sidewards to the W and SW, and to the NE. This caused the northwest tilt of the base of the melaphyric lava sheet on the top of the group, from 1900 m near Giumela in the SE to 1700 m near Do Piz in the NW. This differential sagging is also reflected in the height of the upper pliocene terrace deposits, west of la Greppa, which are about 100 m lower now than the corresponding deposits northeast of Col Bel.

The cross section of the dome resembles — though in a more pronounced form — the experimental pattern of settlement of a model dam on plastic gelatin, given by Krynine (1947, p. 267). The drainage of the top area of the dome coincides with the subsided parts of the centre. In plio-pleistocene time the Giumela river probably flowed through the windgap at 2065 m north of Giumela, later to be captured and deflected to the SSW by a tributary of the Rio di S. Nicolò.

## VII, 5. THE DOME OF CAMPOLONGO.

The ellisoidal, low region in the centre of the Dolomites east of the Sella group with an area of 77 sq. km is a morphologic unit. The long axis of the region runs NW-SE and is about 10 km long, the other axis is 8 km. The area is bounded by the rivers Riotorto and Gadera in the NW, the Rio di San Cassiano in the NE, the Cordevole in the S and the tributary of the latter, the Rio di Andraz, in the east. This area will be called the dome of Campolongo after the pass at its west side. It is not only a unit in a morphographic sense but also more or less a tectonic unit (a collapsing dome) as will be discussed in this subchapter.

The area has now a large, saucer-shaped structure. The oldest rocks, intensly deformed Lower and Middle Triassic, are exposed along the northwestern and southern edges. The centre of the region is composed of the gently inward dipping ladinian volcanic series, overlain in the east by the small ladinian reef Settsass, Raibl strata and Hauptdolomit.

Parts of the Campolongo area were investigated by Mojsisovics (1879), Ogilvie Gordon (1929), Nöth (1929), Signorini (1951), and Accordi (1959). Mutschlechner (1933) published a monograph on the region.

The surface of the Campolongo area is the late pliocene erosion surface and has a mean altitude of 2100 m. The reef mass Settsass is the highest point and rises to 2575 m. The groups of the Sella, the Puez-Gardenaccia, the Fanes and the Lagazuoi with altitudes of 3000 m and more surround the Campolongo region to the west, northwest and northeast. The southern part of this high peripheral rim is the Padon range, south of the Cordevole Valley which is composed of ladinian volcanic rocks.

The ladino-carnian Sciliar dolomite is replaced by the synchronous facies of the marine, clastic and volcanic La Valle and San Cassiano strata in the Campolongo region. A foundering circuit of the dolomite masses around the region started in the early Tertiary as soon as the erosion had removed enough of the counter weight in the surrounding valleys to exceed the threshold value for the stress gradients needed for the initiation of the tectogenetic movements. The plastic upper permian and lower triassic strata beneath the surrounding dolomite masses were squeezed towards the "outlet" in the Campolongo region, where a dome bulged up (see chapter VI, 4 and fig. 10). From the top of this dome sheets of Liassic and Hauptdolomit slid to the centre of the subsiding Sella group. The dome must have existed already in late oligocene or early miocene time (I) because the thrust sheets which slid from its flanks cover the Sella plateau of oligo-miocene age; and (2) because in miocene time the necessary connection for gravity sliding between

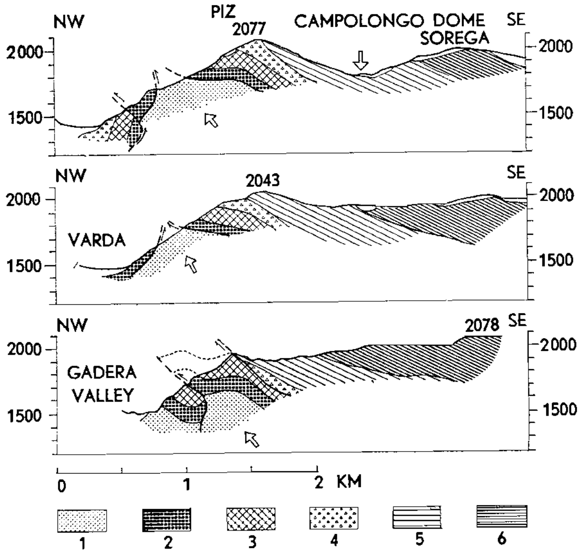



Fig. 47 Sections of the diapiric window at the NE side of the collapsing Campolongo dome, modified after Mutschlechner (1934, sections on the map). 1. Werfen formation 2. Anisian 3. Livinalongo strata 4. agglomerates 5. La Valle strata 6. San Cassiano strata.

the dome and the Sella plateau was already interrupted by erosion down to the lower lying Raibl erosion level which is of miocene age (see Nangeroni, 1938, p. 20).

The rise of the dome caused a more or less annular drainage pattern around the centre. This determined the lay-out of the present oval-shaped drainage system (a similar development was found for the Buffaure dome in the Fassa area).

The carving of the valley system around the dome affected the edges of the outer rim of rigid dolomites, causing collapses of the sides of the Sella and Lagazuoi groups. This effect appears in the east side of the Sella group by the subsidence along a series of N-S striking step faults (see chapter VI, 2). A comparable subsidence is found at the east side of the bulge where the reef masses of the Settsass and the Sasso di Stria are separated by the normal Falzarego-Valparola fault with a throw of 800 m from the Lagazuoi group (see Mutschlechner, 1933, p. 218-219). The fault bifurcates near the Falzarego pass. The main branch separates the Lagazuoi and Tofane groups from the subsided dolomite area to the SW. This fault which runs from the upper San Cassiano Valley over the Falzarego pass into the Boite Valley (see Signorini's map, 1951) belongs to the set of NW-SE striking faults of the northeastern Dolomites (fig. 28), which were discussed in chapter VI, 3. The other branch is a smaller, transversal fault in the elongate Settsass-Nuvolau-La Rochetta unit, which separates the northeastern part of this unit from the subsided Nuvolau group. The fault branches off from the

Falzarego pass where its throw is about 400 m into the Andraz Valley and disappears there (Ogilvie Gordon, 1934, p. 184).

The Campolongo dome with its characteristic peripheral valley system has still another typical feature of diapiric structures: the presence of subsided blocks of the roof in its crest. The arching up of the roof of the diapiric bulge caused tension faults and the local subsidence of "copestone" blocks. The relatively low structural position of a block of Hauptdolomit with abnormal contacts at 2000 m near Suores can thus be understood as a copestone block, which sank down as a wedge — bounded by normal faults — into the crest of the dome.

During the Miocene and lower Pliocene the dome was eroded down to the late pliocene erosion level of 2100 m. Important parts of that surface are still present in the Campolongo region (Piz, 2077 m; Pralongia, 2139 m; Sora Cengle, 2082 m and 2106 m).

Fluvial erosion in the upper Pliocene and Quaternary carved the steep valleys of the Gadera, the Cordevole, and the Rio di San Cassiano around the truncated dome. In the youngest stage of evolution this erosion provided a way of sideward escape for the plastic contents of the dome. Consequently the dome began to collapse by the extrusion of matter in horizontal diapirs and diapiric zones in the sides of the surrounding valleys. A diapiric window of 2 x 0,5 sq. km in the east side of the Gadera Valley (Val Badia) between Corvara and La Villa shows northwest directed deformations of Werfenian and Anisian in a frame of clastic and volcanic La Valle strata (fig. 47).

The same movement patterns were found in the north side of the Cordevole Valley, though they are more complicated in detail there. The lateral diapirism is restricted to small horizontal diapirs between Arabba and Masarei. These diapirs are arranged in three levels, which represent the successively younger stages of diapirism as the local base level of the extrusions was lowered by the progressive carving of the valley floor (see also the chapters VII, 3 and VII, 4). The outcrops of large, chaotic masses of Werfenian and Anisian in the ladinian series were interpreted by Cornelius-Furlani (1929), Mutschlechner (1933), Leonardi (1955), and Accordi (1959) as triassic volcano-tectonic complications. However, the same objections as in the similar case of the Buffaure area can be advanced against this concept of volcano-tectonic origin (see chapter VII, 4).

The oldest of the horizontal diapirs (not so well exposed) is situated at the altitude of 1800-1870 m along the pass road from the Campolongo pass to Arabba. Another diapiric window of this stage (area 90 x 250 m) is in the slope of the Cordevole Valley north of the small village Varda (see figure 48 and figure 49). The terrace at 1780-1800 m at the base of the diapir and a 2 m thick deposit of gravel at 1780 m along the pass road east of the outcrop (exposed in a temporary road cut) are the relics of the old valley floor, which served as a local base level for the diapiric extrusions in the latest part of the Pliocene (see chapter IV, 2 on the age of the terraces).

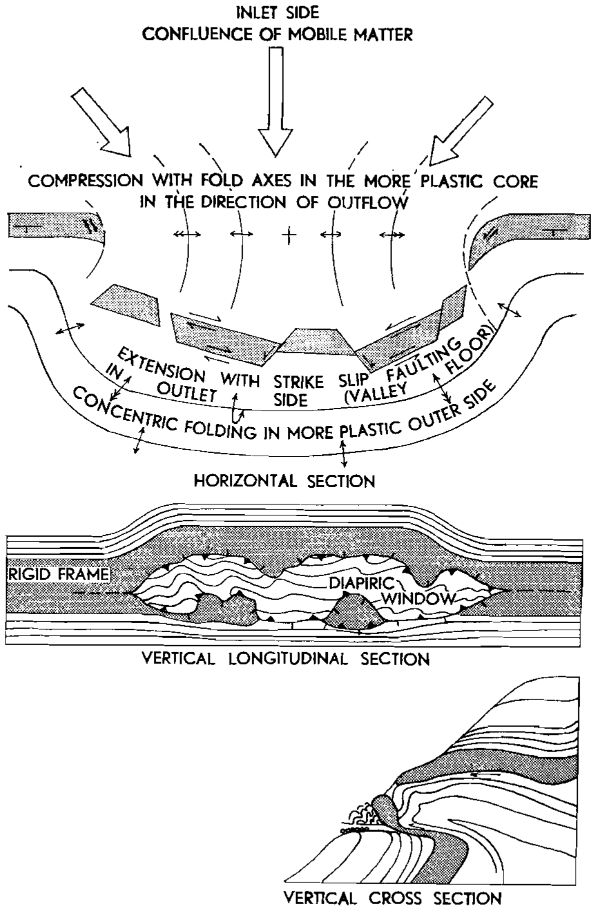



Fig. 48 Scheme of lateral diapirs in valley sides with possible structural elements, based on outcrops in the Badia, Cordevole and Fassa valleys.

After a period of renewed vertical erosion another broader valley floor was eroded down to a level of 1680-1690 m. Terrace relics of it are preserved in the slope west of Varda. About 200 m NNE of the same village a small diapir of Werfenian and of Anisian crops out over some tens of meters. This diapir was formed during a stage of rest in the carving activities of the river.

Remnants of a next younger and deeper valley floor are present at 1520-1530 m, southeast of Varda and near Federa. In a broad and uninterrupted belt plastic Werfenian was squeezed forward and it was thrust over Ladinian, Anisian and Werfenian strata in the northern side of the Cordevole Valley, downstream the village of Masarei at 1500-1600 m above sea-level.

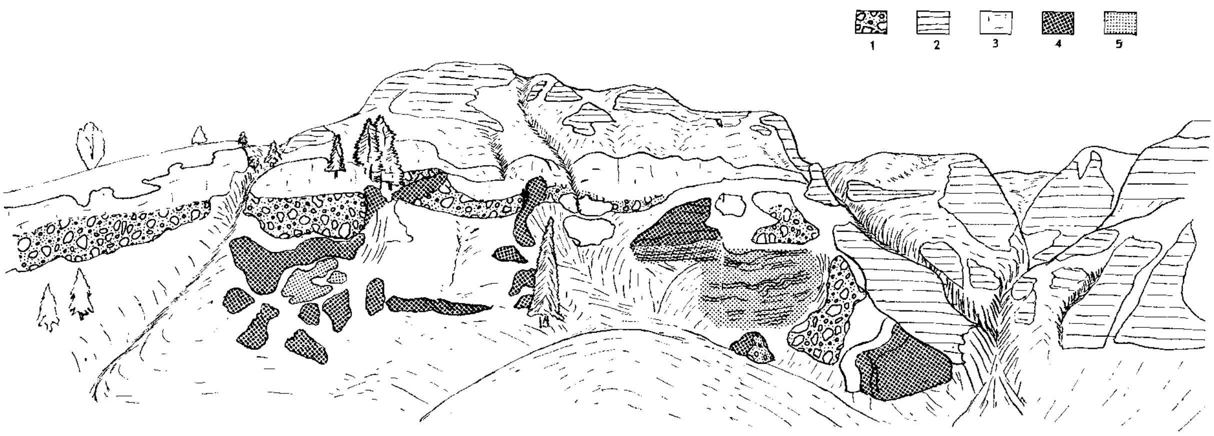



Fig. 49 Sketch of the lateral diapir in the northern valley side of the Cordevole Valley, N. of Varda. The width of the diapir is about 150 m. 1. pleistocene, cemented scree deposits 2. well-bedded volcanic, La Valle strata 3. fine-grained La Valle tuffites 4. anisian dolomite and limestone 5. plastic Werfen formation.

The diapirism has become so important that the whole northern limb of the Cordevole anticline (which follows exactly the course of the river) was intensively folded. This complicated zone, known as the "Line of Livinalongo" appears to be a zone of diapiric, SSW and SW directed, recumbent folds, which are arranged en échelon and which are partly broken and imbricated. It will be discussed in the next subchapter (VII, 6).

## VII, 6. THE CORDEVOLE ANTICLINE, RESULTING FROM THE INCISION OF THE CORDEVOLE VALLEY.

The floor of the Cordevole Valley coincides with an anticlinal axis from Arabba to Caprile. This strict coincidence of the tectonic structure with the curved river course is not accidental. It results from the genetic relation between the young erosional carving of the river and the vertical rise of a diapiric anticline.

The young cenozoic erosion of the river valley caused a reduction of the vertical load, thus creating an elongate minimum of potential energy with its central line at the deepest point of the valley. The plastic strata below the valley bottom are subjected to a sideward and upward pressure, caused by the weight of the pile of rocks on both sides of the river. A diapiric anticline which closely follows the river was formed by this local foundering mass circuit, which resembles a hydraulic press system.

Accordi (1959, p. 25) found that the mean plunge of the anticlinal axis is the same as the slope of the valley bottom (see also De Sitter, 1956, p. 252). This is indeed the situation to be expected in the case of a symmetrical stress field (fig. 16, b) as was found in the Badia Valley along the Gadera (see chapter VI, 4). However, if the local stress field is influenced by another stress field with greater regionality, both influences will give rise to an asymmetric structure.

This situation existed in the Cordevole anticline. Its northern limb is imbricated and folded by the southward directed stress gradients along the southern margin of the collapsing Campolongo dome; whereas the plastic matter at its southern limb flowed mainly to the core of the box-like Padon anticline (see map, fig. 53), which is a younger complication within the large, diapiric Marmolade bulge (see chapter VII, 7).
The complicated northern limb of the Cordevole anticline at the southern border of the Campolongo dome continues in the area with plastic permo-triassic, clastic and volcanic rocks in front of the dolomite masses of Nuvolau-Rochetta. The NW-SE striking strip of dolomites Sass di Stria-Nuvolau- la Rochetta subsided and joins at the northeastern end the edge of the Campolongo dome. The stress field with larger regionality, resulting from this subsidence, caused strong contortions with often isoclinal folds and S and SW-ward movement in the region in front of the blocks between the Andraz Valley and Caprile. The region can be considered to represent the northeastern limb of the Cordevole anticline (fig. 50 and 51).

Moreover, this stress field of greater regionality was superimposed on the more local stress field along the river, which explains the pronounced asymmetry of the Cordevole anticline between the Andraz Valley and Caprile. The roof of Anisian was thrust over the southwestern limb

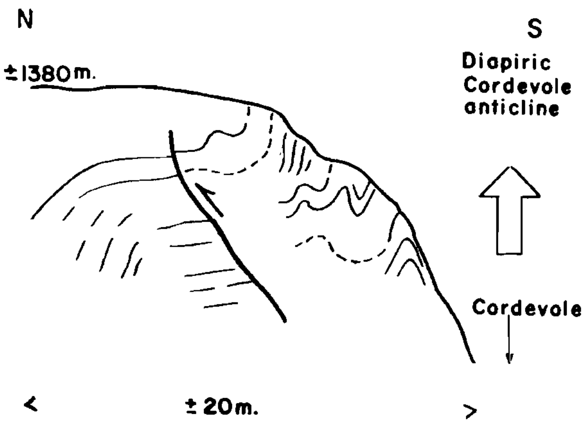



Fig. 50 Detail section of the diapiric Cordevole anticline in the slope below Livrive.

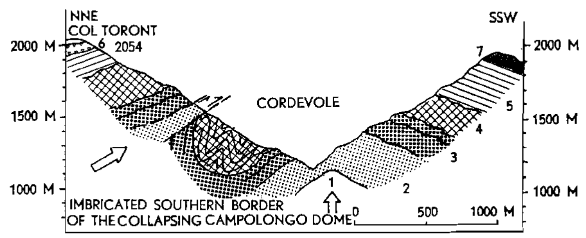



Fig. 51 Section of the imbricated southern border of the collapsing Campolongo dome and of the young cenozoic Cordevole anticline which follows the course of the river, modified after Accordi (1959, section on his map). 1. Bellerophon formation 2. Werfen formation 3. Anisian 4. Livinalongo strata 5. La Valle strata 6. ladinian agglomerates 7. ladinian lavas.

of San Cassiano strata at the Sasso di Rocca. The axis of the diapiric anticline plunges steeply to the SSE at 1 km north of Caprile. Folds with NW-SE striking axes in Werfenian are present in a zone parallel to the diapiric contact with the ladinian tuffs.

An echelon arrangement of the culminations and depressions seems characteristic for such elongate diapiric areas along major valleys. This feature was observed for instance in the pattern of extrusion in the Col Rodella area (see chapter VII, 3 and fig. 42) and by Agterberg (1961, sheet III a) for the Eggerberg structure in the quartz phyllites of the Pusteria Valley.

The Cordevole anticline is another example of this phenomenon (see Accordi's map, 1959) where the outcrops of Bellerophon in the western part of the anticline and the recumbent folds in the Livinalongo strata show echelon arrangement. The entire anticline of Cordevole repeats this pattern on somewhat larger scale near Caprile. The anticlinal core of Werfenian plunges north of Caprile and reappears between Caprile and Alleghe, where the axis is shifted over 500 m to the NNE parallel to its strike. The diapiric character of this culmination is proved by the presence of abnormal contacts around the structure and the existence of folds with converging directions of deformation on either side of the axis. These folds are exposed in the cross section of the anticline along the road from Caprile to Selva di Cadore (see fig. 52 and the map of Ogilvie Gordon, 1934). The river Cordevole switches with a sharp bend north of Caprile from the anticlinal to the synclinal axis of the echelon structure. The river was probably fixed in its synclinal position by the swift rise of the shifted culmination NNE of its course.

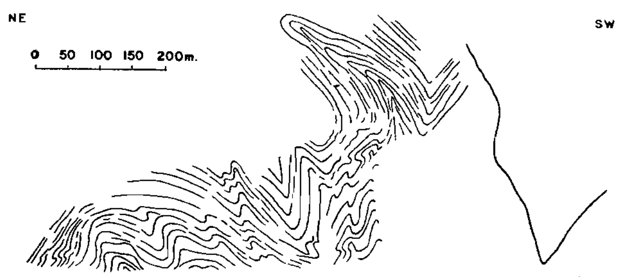



Fig. 52 NE-directed folds in Livinalongo strata along the road Caprile-Selva di Cadore.

## VII, 7. THE MARMOLADA DOME STRUCTURE.

The Marmolada group in the centre of the western Dolomites is limited by the upper Fassa Valley and the Cordevole Valley to the NW and N and the San Pellegrino and Biois Valleys to the south. The Marmolada group is composed of a faulted and folded ladino-carnian reef mass, in the centre of which crops out a core of intensly deformed plastic upper permian, lower and middle triassic strata. Volcanic formations, mainly of ladinian age, surround the reef to the north, northwest and east. Along the southern border strongly folded upper permian and lower triassic rocks and the dioritic and gabbroid intrusive Cricoletta mass are found.

Von Richthofen (1860), Salomon (1895), Mojsisovics (1879), Cornelius and Cornelius-Furlani (1924, 1927), Dal Piaz (1944), Leonardi (1948, 1955), Decima (1951), Morelli and Mosetti (1958), Accordi (1959) and Rossi (1960) published studies on the whole area or parts of it. The tectonic studies of the northern and central areas by Cornelius and Cornelius-Furlani (1927) and of the southern border (Costabella-Valfredda-Ombretta) by Rossi (1960) are the most important from a tectonic point of view and they provide good sections. In the excellent map "Carta geologica della Val di Fassa e dei gruppi dolomitici circostanti" (Leonardi et al. 1961) previous data and the results of unpublished italian surveys were compiled.

The area is characterized by a series of W-E and SW-NE striking folds and faults. Leonardi (1955, 1963) considers them to be formed mainly by regional compression. Some arguments against his hypothesis are advanced:

(1) Opposed directions of tectonic transport are observed, for instance:

a) northward movements in the anticlinal structure of Soura Sass, south of the Cordevole Valley (see Leonardi, 1955 a, profile fig. 9);

b) southward movements in the southern border (Costabella);

c) northward folds in the plastic Triassic of the northern Contrin area.

(2) Normal tensional faults are observed at the north side of the Fedaja Valley; in the zone of the syncline of Forca along the northern border of the Costabella-Valfredda-Ombretta range (Cornelius and Cornelius-Furlani, 1927, p. 61; Rossi, 1960).

(3) The horizontal movements are very limited and probably at most some hundreds of meters (Cornelius and Cornelius-Furlani, 1927, p. 75).

(4) The tectonics of the other dolomitic groups N and NW of the Marmolada group appeared to be formed by local gravity tectonics (see chapter VII, 1-6 and VII, 8). Thus these groups could not transfer the hypothetical southward stress, which is necessary when the structure of the Marmolada group is explained by regional tangential stresses.

The tectonics of the Marmolada group can be understood when considered as the result of the combination of a regional, gravitative stress field and a local gravitative stress field. The more regional stress field is caused by the tendency for southward décollement or sliding of the sedimentary epiderm on the flank of the rising alpine geanticline (see also chapter VI, 3). The more local stress field has a diapiric character, and it caused the subsidence of the edges of the heavy reef mass around a rising diapiric core of plastic Permo-Triassic with lower specific weight.

After an initial stage of non-piercement doming in the Oligo-Miocene the reef mass broke into blocks in the Miocene and Pliocene. These blocks were tilted and rotated towards the diapiric core. The structure of the group is now asymmetric with a tendency to form southward imbricated monoclines on account of the superposition of the regional gravitative stress field on the local diapiric mass circuit. The diapiric core with non-resistant rocks was truncated by the late pliocene erosion surface. Renewed diapirism in the youngest Pliocene and afterwards was induced by the reactivated vertical erosion; this resulted, for instance, in the formation of a pile of thrust masses at the Col Ombert on the late pliocene erosion surface. These masses slid from the top of the diapiric culmination at the Passo di San Nicolò, which belongs to the greater unit of the Contrin diapir (the centre of the Marmolada structure). This concept of the structural development of the Marmolada group will now be discussed more in detail.

**The oldest stage: non-piercement doming**

The Marmolada reef plate must have been pushed up already during the Oligocene into a broad swell of about 15 x 12 km with its long axis in east-west direction. The rise of this swell was partly due to the tendency to form undulatory structures in the tilted epiderm on the southern limb of the alpine geanticline, which rose since the early Tertiary. Moreover, a confluence of the permian gypsum to a dome under the influence of the weight of more than 1000 m of sediments is probable. This is indicated also by the presence of gypsum within the diapiric core of Contrin. Another supply of matter for the Marmolada bulge came from beneath the subsiding Sella group, which had already subsided about 350 m before the Oligo-Miocene (see chapter IV, 2 and VII, 2). This subsidence of the Sella group was compensated partly volumetrically by the rise of the Marmolada bulge.

The oligo-miocene erosion surface was cut in the Norian in the Sella group, but it truncates the Marmolada group in the level of the older Marmolada limestone (comparable to the Sciliar dolomite, see chapter IV). This fact indicates that the Marmolada group formed already a bulge in early tertiary time. Moreover, the presence of this bulge

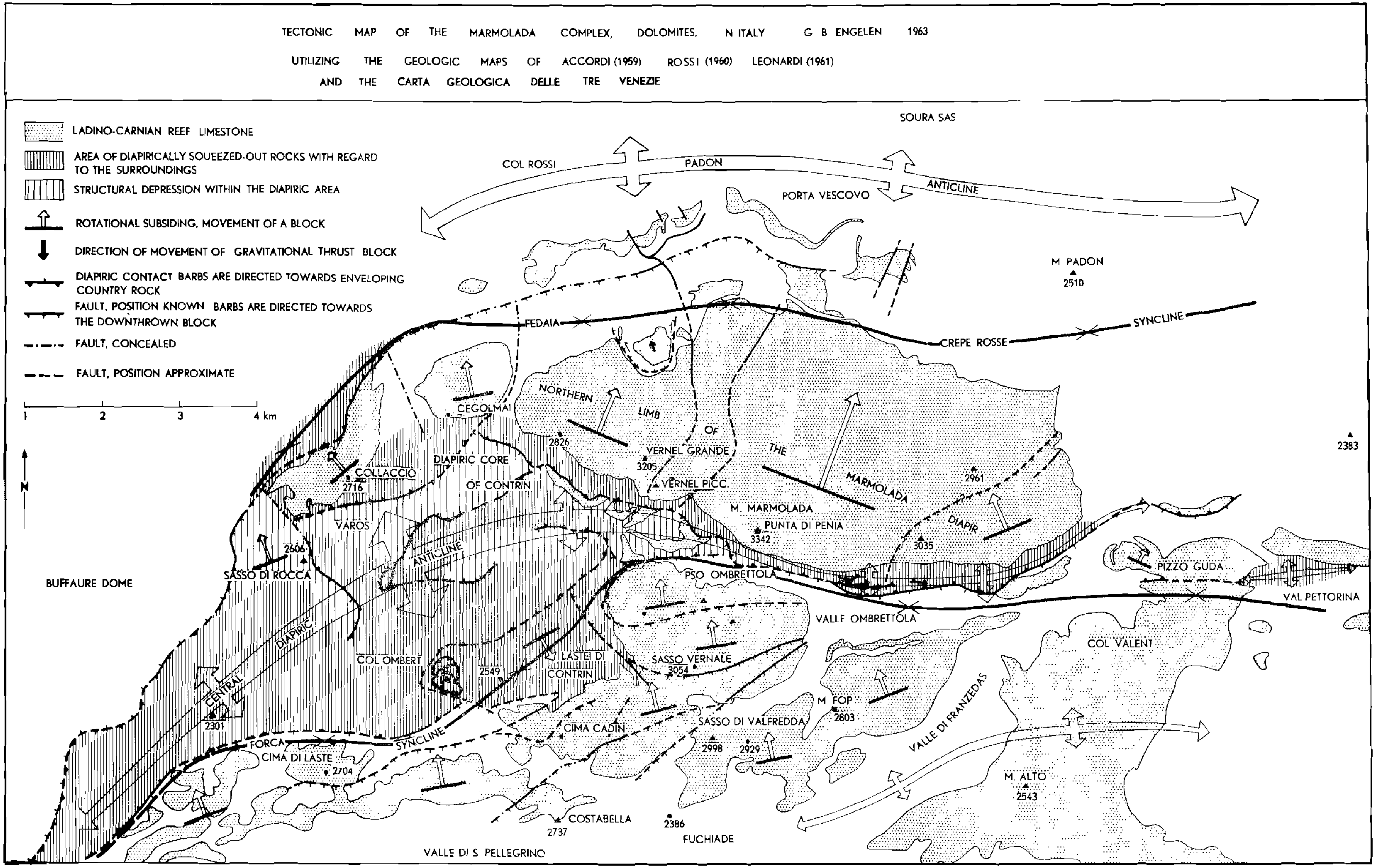

TECTONIC MAP OF THE MARMOLADA COMPLEX, DOLOMITES, N ITALY G B ENGELEN 1963
UTILIZING THE GEOLOGIC MAPS OF ACCORDI (1959) ROSSI (1960) LEONARDI (1961)
AND THE CARTA GEOLOGICA DELLE TRE VENEZIE
LADINO-CARNIAN REEF LIMESTONE
AREA OF DIAPIRICALLY SQUEEZED-OUT ROCKS WITH REGARD TO THE SURROUNDINGS
STRUCTURAL DEPRESSION WITHIN THE DIAPIRIC AREA
ROTATIONAL SUBSIDING, MOVEMENT OF A BLOCK
DIRECTION OF MOVEMENT OF GRAVITATIONAL THRUST BLOCK
DIAPIRIC CONTACT BARBS ARE DIRECTED TOWARDS ENVELOPING COUNTRY ROCK
FAULT, POSITION KNOWN BARBS ARE DIRECTED TOWARDS THE DOWNTHROWN BLOCK
FAULT, CONCEALED
FAULT, POSITION APPROXIMATE
1 2 3 4 km
N
SOURA SAS
COL ROSSI
PADON
ANTICLINE
PORTA VESCOVO
M PADON
2510
FEDAIA
CREPE ROSSE
SYNCLINE
NORTHERN LIMB OF THE MARMOLADA DIAPIR
CEGOLMAI
2826
VERNEL GRANDE
3205
VERNEL PICC.
M. MARMOLADA
PUNTA DI PENIA
3342
2961
3035
2383
DIAPIRIC CORE OF CONTRIN
COLLACCIO
2716
VAROS
ANTICLINE
2606
SASSO DI ROCCA
BUFFAURE DOME
PSO OMBRETTOLA
VALLE OMBRETTOLA
PIZZO GUDA
VAL PETTORINA
CENTRAL DIAPIRIC
COL OMBERT
2549
LASTEI DI CONTRIN
SASSO VERNALE
3054
COL VALENT
M FOP
2803
VALLE DI FRANZEDAS
2301
FORCA
CIMA DI LASTE
2704
SYNCLINE
CIMA CADIN
SASSO DI VALFREDDA
2998
2929
M. ALTO
2543
COSTABELLA
2737
2386
FUCHIADE
VALLE DI S PELLEGRINO

Fig. 53

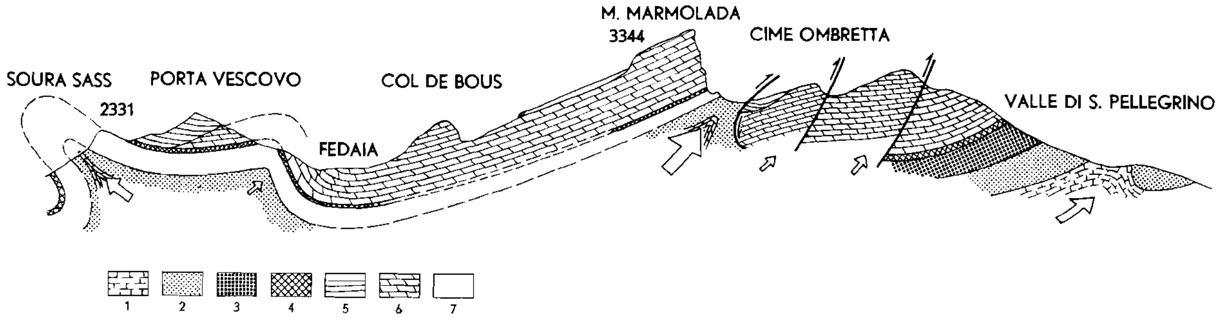



Fig. 54 Section of the Marmolada group, partly after Leonardi (1955, a, fig. 9). See also fig. 14 for comparison with an experiment of Ramberg. 1. Bellerophon formation 2. Werfen formation 3. Anisian 4. Livinalongo strata 5. La Valle strata 6. Marmolada limestone 7. glacier.

explains the origin of the thrust sheets (slides) on the Sella plateau, which came partly from the northern limb of the Marmolada bulge (Soura Sass area). See fig. 14 and 54.

### The younger stage: diapiric piercement

Vertical erosion prevailed during the Miocene and the lower Pliocene. Meanwhile the Marmolada bulge came in its piercement stage of development. The bulge evolved into a diapir, which implies a collapse of the original domal structure and its dissection into many smaller units. At present — after the collapse — the following zones can be distinguished from north to south (see map, fig. 53):

a) the Padon anticline, a box fold with diapirically pierced flanks
b) the Fedaja-Crepe Rosse syncline
c) the broken northern limb of the Marmolada diapir
d) the diapiric core of Contrin with its eastern extension in the upthrusts at the base of the southern scarp of the Marmolada
e) the broken and southward imbricated limb of the Marmolada diapir.

### The Padon anticline

The Padon anticline is a boxlike anticline with an E-W axis, between the Cordevole, Avisio and Fedaja Valleys. It is the northern fringe of the initial Marmolada bulge. With the collapse of the bulge, the main mass of the Marmolada reef at the north side subsided, rotated and tilted to the north along a flexure/syncline through the upper Avisio and the Fedaja Valley. An anticlinal structure parallel to the axis of the bulge was thus separated from the main unit. The greater part of the plastic matter underneath the northern limb of the bulge flowed to the south, but the Padon anticline acquired the form of a box fold. This fold has now diapirically pierced limbs at both sides. Its limbs are locally overturned, broken and pierced by the older, upper permian and triassic strata. Such a small northward directed diapir is the anticline of Soura Sass with its core of Bellerophon (see Accordi, 1959, for a map and a section). A careful study of the southern limb in the Avisio and Fedaja Valleys between Penia and the artificial lake Fedaja reveals that the irregular outcrops of Werfenian and Anisian are also mainly small diapiric windows formed in young cenozoic time, instead of being volcano-tectonic dislocations of triassic age as was supposed by Cornelius and Cornelius-Furlani (1924), Leonardi (1955) and Accordi (1959).

### The Fedaja-Crepe Rosse syncline

A slightly curved syncline follows the Avisio Valley from the confluence of the Rio di Contrin with the Avisio to the east, through the Fedaja Valley into the Crepe Rosse, south of the M. Padon. This syncline or flexure with steep northern limb (the southern limb of the Padon anticline) separates the northern part of the initial bulge from the central area. It was formed as a result of the tilt of the Marmolada block south of it. The syncline fades out in eastern direction. Its southwestern extension is the normal fault to the NW of the Collaccio block, where now a diapiric fringe of Werfenian is found (see profile fig. 55).

### The northern limb of the Marmolada diapir

The rigid reef plate on the northern limb of the central diapiric zone broke into blocks, which subsided and rotated towards the centre. The blocks have normal faults or the flexure-like Fedaja-Crepe Rosse syncline in the rear and small upthrusts in front, along the southside where the plastic underlying triassic rocks were squeezed out. The blocks of Collaccio, Cegolmai, Pala di Vernel, Punta di Penia, and Piz Serauta are such individual units.

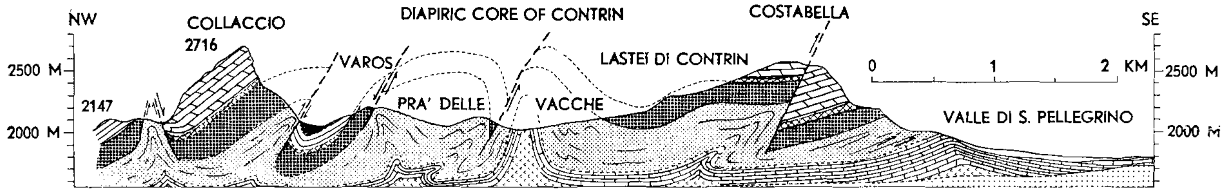



Fig. 55 Section of the Marmolada group with a diapiric fringe at the NE side and the central diapiric area of Contrin.

## The central diapiric area

The area of Contrin with its contorted upper permian and triassic strata represents the core of the Marmolada diapir. It extends to the east in the upthrusts along the base of the Marmolada scarp and the small diapiric culminations west and east of the Piz Guda. The central diapiric area continues to the southwest along the Costabella range to the intrusive Cricoletta mass. The diapiric core of Contrin shows the centrifugal movement pattern, which is so characteristic for diapirs. Northward directed minor folds occur at the north side of this large diapiric window; southward directed folds were observed along the southern border. Werfenian was thrust away from the centre over the ladino-carnian volcanics south of the Sasso di Rocca. Another common phenomenon of diapirism is the alternation of lense-shaped structural high and low areas within the diapiric core (see chapter VII, 6). Less uplifted lenses of Anisian and ladino-carnian volcanics between Varos and the Pala di Vernel, and of Anisian north of Pra delle Vacche are such structural depressions in the roof of the diapir (see fig. 55). The complicated mixture of Anisian and volcanics west of the Pala di Vernel might be a triassic eruption centre, though the possibility that the mixing is a result of diapirism is not excluded.

## The local complications of the Col Ombert

Leonardi (1948, b) described some small superposed thrust masses of Anisian and Livinalongo strata along the southern border of the Contrin diapir at the Col Ombert. He concluded from the observed repetition of upper and lower Anisian that three northward upthrusts are present here. Rossi (1960) suggested sliding as an explanation for the structures in the upper part of the mountain, which consists of Livinalongo strata, but he still thought that the structures were mainly the result of compression.

Closer observations showed that Leonardi's observation of the stratigraphic repetition is indeed correct, but his tectonic interpretation as northward upthrusts is not confirmed by our field data. In our opinion these slices of Anisian slid successively southward from the top of the adjacent diapiric culmination at the San Nicolò pass to the north (see fig. 56). These slide slabs were piled upon one another. This phenomenon of diverticulation (see chapter VII, 2) with its southward overthrust and folded strata is visible looking from the Lastei di Contrin to the west. The Col Ombert, composed of the small thrust sheets, is an abnormal high and steep mass (2670 m) at the westside of the rather flat late pliocene erosion surface which is well preserved in the calcareous Anisian of the Lastei di Contrin at about 2200-2300 m above sea-level. The sheets of the Col Ombert unconformably rest upon the late pliocene erosion surface; the case is comparable to the abnormal position of the Piz Boè mass on the Sella plateau (see chapter VII, 2). Thus the age of these local gravity slides can be fixed as post upper-pliocene. The area of the Passo di San Nicolò, less than 1 km north of the Col Ombert, is one of the smaller structural culminations within the diapiric core of Contrin. The presence there of the oldest rocks of the group (Bellerophon gypsum) cropping out at an altitude of 3250 m above sea-level proves this diapiric culmination.

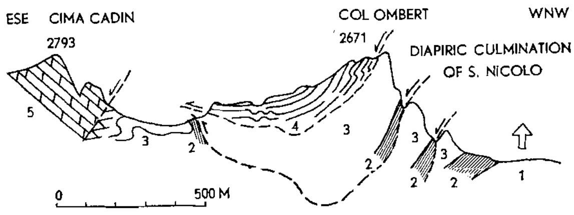



Fig. 56 Section of the Col Ombert (Marmolada group), south of the Passo di San Nicolò. The Col Ombert is composed of a pile of local thrust sheets which slid from the diapiric culmination of San Nicolò which is a part of the diapiric core of Contrin. 1. Werfen 2. lower Anisian 3. upper Anisian (limestone of Contrin) 4. Livinalongo strata 5. Marmolada limestone.

The increase of the vertical erosion after the formation of the late pliocene erosion level will have induced a renewed subsidence and rotation of the surrounding dolomite blocks towards the central diapir. The small diapiric culmination of the Passo di San Nicolò with the related sliding phenomena were the result of these younger movements.

**The broken, southward imbricated southern limb of the Marmolada diapir**

The Costabella-Valfredda-Ombretta range is the southern limb of the Marmolada bulge. Rossi (1960) dedicated a tectonic study to it and found that it is made up of imbricated, northward dipping monoclines of ladino-carnian reef limestone and dolomite. Moreover, he observed a syncline (the Forca syncline) between the central anticline and the southern border of monoclinal blocks. The northern limb of this syncline is composed of the plastic Triassic and the Anisian of the central Marmolada diapiric anticline; the southern limb is formed by a northward dipping monocline of reef limestone and dolomite.

We consider this syncline which is locally a subsided zone between normal faults (Rossi, 1960, profile 8), as the marginal depression along the southside of the central diapiric area of Contrin. The zone of imbricated monoclines represents the southern foot of the Marmolada bulge which existed during the Oligocene and Miocene. This foot acted as a buttress supporting the original Marmolada vault in its non-piercement stage of development. It then collapsed under the local stress field and it was transformed into an imbricated structure with southward directed upthrusts. The underlying Permo-Triassic was pressed to the south towards the Pellegrino and Biois Valleys, where important minor deformations in these strata occur (see Rossi, 1960, profile 2).

## VII, 8. GRAVITY TECTONICS IN THE EASTERN DOLOMITES.

There is no generally accepted limit between the western and eastern Dolomites. Signorini (1951) considers the area east of the rivers Gadera and Cordevole as eastern Dolomites, whereas for Accordi (1957) the Sorapis and Croda Rossa groups, which lie east of this limit, still belong to the western Dolomites (see also our opinion at the end of subchapter VI, 3).

The influence of gravitational subsidence on the tectonics of the Dolomites was already suggested by Diener (1900) at the beginning of this century. Similar views were expressed by Mojsisovics as early as 1879. Kober (1908, p. 243), however, accepted only a subordinate role of gravity tectonics in the eastern Dolomites.

Signorini (1951, 1955) was the first who tried to re-evaluate the data on the eastern Dolomites on the basis of modern concepts of mountain building, which concepts attribute a dominant role to gravity tectonics. He tried to get rid of the powerful influences exerted upon geologic thinking by the classic theories of mountain building by means of tangential compression.

The objections of Leonardi (1955, pp. 47-49) — who is still inclined to explain the main tectonic features by tangential compression — against Signorini's ideas are not convincing because he refutes them without discussing the facts advanced by Signorini (1955).

Accordi (1955, 1957) studied the intricate summit thrusts and summit foldings of the Tofane, Fosses, Sorapis, Cristallo, Civetta and Croda Rossa groups and in an excellent study he ascertained their gravitative character. He interpreted these structures, however, as gravity slides of secondary importance, occurring on the limbs of larger, regional folds, which should have been formed by regional, tangential compression during the alpine mountain building.

Agterberg (1961, p. 70) proved the gravitative character of the southward movement of the Tudaio mass SE of Auronzo.

Our investigations in the western and eastern Dolomites in general confirm the validity and correctness of Signorini's concepts.

A summary of Signorini's ideas follows, because his views are important but not so easily accessible to those not acquainted with the italian language:

1) The tectonic units of the eastern Dolomites are mainly monoclinal northward dipping blocks of mid — to upper triassic dolomites which become steeper towards the higher frontal part at their southern side. They have a tendency to form southward-directed imbricated structures.

2) The tendency to a steepening of the dip along the front of the blocks in many cases extends towards the sides and even the rear; it results in half saucer-shaped or spoon-shaped structures. This is usually observed of rigid blocks subsiding into a plastic base, and it is the common form in the NW Dolomites, as described in this chapter.

3) In contrast to the simple structures of the dolomitic masses, the underlying permo-triassic strata show very complicated tectonics with repetitions, imbrication, steep folds etc. Differential vertical and horizontal movements between the rigid dolomite masses and their plastic substratum have occurred.
4) Complicated tectonics in the Jurassic and Cretaceous are found on top of the dolomite blocks. These belong to the group of summit thrusts and summit foldings, described by Accordi (1955, 1957).
5) The individual blocks have different strikes and dips in most cases, which makes it hard to explain these structures by uniform S-N tangential compression.
6) The tectonic structures (faults, folds, etc.) do not continue over great distances. They are more local features. This leads Signorini to the concept of a special tectonic style for the eastern Dolomites, comparable to similar phenomena in the Apennines which are due to gravity tectonics. He distinguished the following structural zones, in the eastern Dolomites from north to south:
1) A zone of uplifted crystalline basement (Pusteria Valley), which was tectonically denudated.
2) The northern border of the eastern Dolomites with southward dipping monoclines on the tilted margin of the first zone.
3) A zone of flatlying dolomites (for instance around the Cime di Lavaredo).
4) A large zone of northdipping and southward imbricated monoclines.
5) A series of broad flexure-folds in the Venetian Pre-Alps, which are separated from the Dolomites by a SE-ward upthrust along the Piave line.

The concepts of Signorini could be amplified with data of Agterberg (1961, p. 65) on the tectonics of the quartz-phyllitic basement and by our data. In Signorini's second zone we found southward overturned folds in higher stratigraphic levels (see chapter VI, 3), which confirms the presence of southward directed gravity tectonics. Moreover, a younger second phase with SW-ward gliding was found in that zone. Faulting along a set of NW-SE striking faults divided the area in elongate units which slid to the SW. This phase was induced by the rise of the anticlinal structures of Auronzo and Vallandro, in the basement of quartz phyllites, which are asymmetrical, overturned to the SW (see chapter V, 3 and VI, 3 and Agterberg 1961, chapter II).

We consider the mentioned phenomena in the crystalline basement (mesoderm) and in the sedimentary epidermis as the gravitative reactions to the rising of the alpine geanticline since the early Tertiary. The geanticline has a major subdivision of its southern flank in this part of the eastern Alps along the Pusteria fault, the Val Sugana flexure fault, the Bassano flexure fault and an assumed fault under the Po plain. The geanticlinal flank descends along these faults steplike from the Tauern culmination to the subsided Po and Adria areas. (see De Boer, 1963, fig. 39 on p. 132).

## LITERATURE REFERENCES


ACCORDI, B. (1955, a) — Le dislocazioni delle Cime (Gipfelfaltungen) delle Dolomiti: Ann. Univ. Ferrara. Vol. 2, 2. pp. 65-188.

———, (1955, b) — Stratigrafia e Paleontologia delle formazioni oligo-mioceniche del Trevigiano Orientale. Centro Studi Petr. e Geol. del C.N.R. presso l'Univ. di Padova.

———, (1957) — Nuove ricerche sui corrugamenti di vetta (Gipfelfaltungen) delle Dolomiti Occidentali: Boll. Soc. Geol. Ital. Vol. 76, pp. 3-23.

———, (1959) — Geologia dell' alta valle del Cordevole (Dolomiti): Memorie degli Istituti di Geologia e Mineralogia Univ. Padua. Vol. 21, pp. 1—30.

AGTERBERG, F. P. (1961) — Tectonics of the cristallyne basement of the Dolomites in North Italy: Geologica Ultraiectina, no. 8, Ph. D. thesis Utrecht.

———, (1963) — The method of statistical structural analysis (as applied to the cristallyne basement of the Dolomites in North Italy): Geol. en Mijnb., in press.

AMPFERER, O. (1929) — Einige Beispiele von Kerbwirkung und Reliefüberschiebung aus den Südtiroler Dolomiten: Jahrb. Geol. B. Anst. Wien, 79, pp. 241-256.

AS, J. A., and ZIJDERVELD, J. D. A. (1958) — Magnetic cleaning of rocks in paleomagnetic research: Geoph. Journ. Royal Astr. Soc. Vol. 1, 4.

BEHNKE, Cl., GIESE, P., PRODEHL, Cl., VISINTINI, G. DE, (1962) — Seismic refraction investigations in the Dolomites for the exploration of the earth's crust in the eastern alpine area, 1961: Boll. di Geof. teor. ed applicata, Vol. IV, N. 14, pp. 110-132.

BEMMELEN, R. W. VAN (1931) — De bicausaliteit der bodembewegingen: Nat. Tijdschr. voor Ned. Indië, Deel XCI, Afl. 3, pp. 363-413.

———, (1950) — Cosmogony and geochemistry. 18th Int. Geol. Congr. Britain 1948, Vol. 11, pp. 9-21.

———, (1952) — Gravity field and orogenesis in the West-Mediterranean region: Geol. & Mijnb. Vol. 14, pp. 306-313.

———, (1954, a) — Mountain building. Mart. Nijhoff, Den Haag.

———, (1954, b) — The geophysical contrast between orogenic and stable areas: Geol. & Mijnb., Vol. 16, pp. 326-334.

———, (1955) — Tectogenèse par gravité: Bull. Soc. Belge de Géol., de Paléont. et d'Hydrol. Tome LXIV, Fasc 1. pp. 95-123.

———, (1956) — The geochemical control of tectonic energy: Geol. & Mijnb. N.S. 18, 4, pp. 131-144.

———, (1957) — Beitrag zur Geologie der Westlichen Gailtaler Alpen (Kärnten, Österreich) 1: Jb. Geol. B. Anstalt, 100, 2, pp. 179-212.

———, (1958) — Stromingsstelsels in de silicaatmantel: Geol. & Mijnb. N.S. 20, 1, pp. 1-17.

———, (1960, a) — New views on east alpine orogenesis: Int. Geol. Congr., Proc. 21 st sess., Copenhagen, pt. 18, pp. 99-116.

———, (1960, b) — Die Methoden in der Geologie: Mitt. der Geol. Gesellschaft, Wien, Band 53, pp. 35-52.

———, (1961) — Beitrag zur Geologie der Gailtaler Alpen (Kärnten, Österreich). Die zentralen Gailtaler Alpen: Jb. Geol. B. Anstalt, 104, pp. 213-237.

———, (1963) — Geotektonische Stockwerke. Eine relativistische Hypothese der Geotektonik: Mitt. Geol. Gesellsch. Wien, Band 55, 1962, pp. 209-232.

BOER, J. DE (1963) — The geology of the Vicentinian Alps (S. Dolomites, NE Italy) with special reference to their paleomagnetic history: Geol. Ultraiectina no. 11, Ph. D. thesis Utrecht.

CAREY, S. WARREN (1962, a) — Scale of geotectonic phenomena: (Univ. of Tasmania, Dept. of Geol. Publ. 103): Journ. Geol. Soc. India, 1962, Vol. 3, pp. 97-105.

———, (1962, b) — Folding: (Univ. of Tasmania, Dept. of. Geol., Publ. 95). Journ. of Alberta Soc. of Petr. Geologists. Vol 10, no. 3, pp. 95-144. including: E. S. O' Driscoll: Experimental patterns in superposed similar folding, pp. 145-167.

CITA, M. B. (1955) — Paleogeografia del Terziario nella regione gardesana: Riv. Ital. Pal. e Strat., Vol. 61, no. 3, Milano.

CORNELIUS, H. P., and CORNELIUS-FURLANI, M. (1924) — Zur Geologie der Tuffbildungen im Marmolatagebiet (Südtirol): Centralblatt für Min. Geol. und Pal. pp. 366-373.

———, (1927) — Ueber die Tektonik der Marmolata-Gruppe (Südtirol): N. Jahrb. für Min., Geol. und Pal. Beilageband 56, Abt. B. pp. 1-77.

CORNELIUS-FURLANI, M. (1924) — Zur Kenntnis der Villnösser Linie: Verhandl. Geol. B. Anst. Wien, no. 7, 1924, pp. 125-131.

DAL PIAZ, G. (1944) — La conca della Fedaia. Studio geologico per creazione di un serbatoio idraulico: Mem. Ist. Geol. Padova, Vol. XV, pp. 1-26.

DECIMA, F. P., (1951) — Studi geotettonici sulla Valle Ombretta e sulla conca di Malga Ciapela nel Gruppo della Marmolada: Studi trentini, Vol. XXVIII.

DIENER, C. (1900) — Über den Einfluss der Erosion auf die Structur der Südosttirolische Dolomitstöcke: Mitt. K. K. Geogr. Gesellsch. Wien, Bd. 43, pp. 25-30.

DIETZEL, G. F. L. (1960) — Geology and permian paleomagnetism of the Merano region (Province of Bolzano, N. Italy). Geologica Ultraectina, no. 4. Ph. D. thesis Utrecht.

ECKEL, E. B. (ed.) (1958) — Landslides and engineering practice. Highway Research Board. Special Report 29 Washington D. C. NAS-NRC Publication 544, pp. 232.

ENGELEN, G. B. (1963) — Indications for large-scale graben formation along the continental margin of the Eastern United States: Geol. & Mijnb., 42, pp. 65-94.

EVERDINGEN, R. O. VAN (1960) — Paleomagnetic analysis of permian extrusives in the Oslo region, Norway: Det Norske Videnskaps. Akad. 1 Oslo, Mat.-Naturv., kl. 1960, 1.

FALLOT, P. (1950) — Remarques sur la tectonique de couverture dans les Alpes Bergamasques et les Dolomites: Bull. Soc. Géol. France, 5e ser., 20, pp. 183-195.

FIOR, S. (1957) — Il rilevamento geologico della tavoletta di Castelrotto (Bolzano). Tesi di laurea (unedited) Bologna.

FURLANI, M. (1909) — Zur Tektonik der Sellagruppe in Gröden:
Mitt. Geol. Gesellschaft Wien, II-er Band, pp. 445-461.

HAARMANN, E. (1930) — Die Oszillationstheorie. Eine Erklärung der Krustenbewegungen von Erde und Mond.
Verlag F. Enke, Stuttgart, pp. 260.

HAMILTON, W. S. (1962) — Structural model of large part of the earth:
Bull, A. A. P. G., Vol. 46, no. 5. (May, 1962) pp. 610-639, 12 figs.

HEISSEL, W., and LADURNER, J. (1936) — Geologie des Gebietes von Villnöss-Gröden - Schlern - Rosengarten:
Jb. Geol. B. Anstalt, 86, 1 - 2, pp. 1-63.

HILTEN, D. VAN (1960) — Geology and permian paleomagnetism of the Val-di-Non-area, W. Dolomites, N. Italy.
Geologica Ultraiectina, no. 5. Ph. D. thesis, Utrecht.

———, (1961) — A deviating Permian pole from rocks in Northern Italy. Geoph. Journ. Roy. Astr. Soc. 6, n. 3, pp. 377-390.

———, (1962) — Presentation of paleomagnetic data, polar wandering and continental drift:
Am. J. of Sci. 260, June 1962, pp. 401-426.

HOLLINGWORTH, S. E., TAYLOR, J. H., and KELLAWAY, G. A. (1944) — Large-scale superficial structures in the Northampton Ironstone Field:
Quarterl. Journ. Geol. Soc., London, 100, pp. 1-49.

HUMMEL, K. (1932) — Oberflächennahe Intrusionen und Trümmerlaven in der Süd-alpinen Mitteltrias.
Fortschritte der Geol. und Paleont. Band XI, Deecke-Festschrift, pp. 44-74.

KLEBELSBERG, R. VAN (1935) — Geologie von Tirol. Verlag Borntraeger, Berlin.

KOBER, L. (1908) — Das Dachsteinkalkgebirge zwischen Gader, Rienz und Boita:
Mitt. d. Geol. Gesellschaft Wien, Band I, 1908, pp. 203-244.

KOCKEL, C. W. (1957) — Untervorschiebung, eine vernachlässigte, tektonische Form:
Neues Jahrbuch f. Geol. und Paleont., 1957, pp. 66-71.

KORN, H., and MARTIN, H. (1959) — Gravity tectonics in the Naukluft mountains of South-West Africa:
Bull. Geol. Soc. Am., Vol. 70, pp. 1047-1078.

KRUSEMAN, G. P. (1962) — Etude paléomagnetique et sedimentologique du bassin permien de Lodève Hérault, France.
Geologica Ultraiectina, 9, Ph. D. thesis Utrecht.

KRYNINE, D. P. (1947) — Soil mechanics. 2nd ed. Mc. Graw Hill Book Cy. New York.

LEONARDI, P. (1941) — A proposito dello scorrimento della Cima del Rodella e di una recente publicazione di M. Ogilvie-Gordon e J. Pia:
Studi Trentini di Sc.nat. Rivista d. Soc. di Studi per la Venezia Trident. Annata 22, Vol. 19, 2.

———, (1943) — Sintesi stratigrafica-tettonica e nuova carta geologica al 50.000 della Val Gardena e dei gruppi dolomitici circostanti:
l'Universo, Anno 24, N. 4. pp. 1-39.

———, (1948, a) — Nuove ricerche geologiche nel gruppo della Marmolada (Dolomiti):
Rend. Acc. Naz. Lincei, Ser. VIII, Vol. V, pp. 56-60.

———, (1948, b) — Novità geopaleontologiche-dolomitiche:
l'Universo. Anno 28, N. 6.

———, (1953) — Nuova interpretazione della tettonica della Val di Fassa e scoperta di tronchi silicizzati giuresi nella Valle del Piave:
La ricerca scientifica, 23, N. 8. pp. 1399-1406.

———, (1955, a) — Breve sintesi geologica delle Dolomiti occidentali:
Boll. Soc. Geol. Ital. Vol. 74, 1, pp. 1-140.

———, (1955, b) — Quarta campagna geo-paleontologica nelle Dolomiti:
La ricerca scientifica. Anno 25, N. 3. pp. 553-559.

———, (et al.) (1961) — Carta geologica della Val di Fassa e dei gruppi dolomitici circostanti. (1 : 25.000).
Ed. Ist. Geologico Ferrara.

———, (1961) — Triassic coralligenous reefs in the Dolomites:
Annali dell' Università di Ferrara, Nuova Serie, Sezione IX, Vol. III, N. 8. pp. 127-155.

———, (1962) — Il gruppo dello Sciliar e le scogliere coralligene dolomitiche. Richerche geo-paleontologiche nelle Dolomiti, Ferrara.

———, (1963) — Attraverso le Dolomiti occidentali. Itinerari naturalistici attraverso le Alpi, III. Club Alpino Italiano.
Ed. A. Noseda, Como.

LEONARDI, P. and ROSSI, D (1957) — La scogliera coralligena del Sella nelle Dolomiti Occidentali:
Ann. Univ. Ferrara. Sez. IX, Vol. 3, 1. pp. 1-36.

LINGEN, G. J. VAN DER (1960) — Geology of the Spanish Pyrenees, north of Canfranc, Huesca province:
Estud. Geol. Vol. XVI, pp. 205-245. Ph. D. thesis, Utrecht.

LUGEON, M. (1943) — Une nouvelle hypothese tectonique, la diverticulation (note preliminaire):
Bull. Soc vaud. Sc. nat., Vol 62, no. 260.

MERLA, G. (1932) — Osservazioni morfologiche e tettoniche sugli altipiani ampezzani, (Fosses-Sennes-Fanes):
Atti Soc. Toscana di scienze nat. Vol. 42, pp. 23-64.

MITTEMPERGHER, M. (1958) — La serie effusiva paleozoica del Trentino-Alto Adige:
Studi e ricerche Div. Geom. d. CNRN, Vol. 1, pp. 61-145.

———, (1962) — Rilevamento e studio petrografico delle vulcaniti paleozoiche della Val Gardena:
Atti Soc. Tosc. Sc. Nat., serie A, fasc. II, 1962, pp. 41.

MOJSISOVICS, E. VON (1879) — Die Dolomit-Riffe von Südtirol und Venetien. Wien.

MORELLI, C., MOSETTI, F. (1958) — Ricerche geofisiche per lo sbarramento secondario del bacino della Fedaia. (M. Marmolada):
l'energia elettrica Vol. XXXV, fasc. n. 7, pp. 7.

MUTSCHLECHNER, G. (1932) — Geologie der St. Vigiler Dolomiten:
Jb. Geol. B. Anstalt, 82, 1-2, pp. 163-273.

———, (1933, a) — Geologie der Peitlerkofelgruppe (Südtiroler Dolomiten):
Jb. Geol. B. Anstalt, 83, 1-2. pp. 75-112.

———, (1933, b) — Geologie des Gebietes zwischen St. Cassian und Buchenstein (Südtiroler Dolomiten):
Jb. Geol. B. Anst., 83, pp. 190-232.

———, (1935) — Geologie der Langkofelgruppe:
Jb. Geol. B. Anstalt 85, pp. 21-49.

NANGERONI, L. G. (1938) — Morfologia del Gruppo di Sella e della regione Barbellino:
Public. d. Univ. Cattol. d. Sacro Cuore, Serie X, Vol. 11, ed. „Vita e pensiero", Milano.

NÖTH, L. (1929) — Geologie des mittleren Cordevolegebietes zwischen Vallaza und Cencenighe (Dolomiten):
Jahrb. Geol. B. Anstalt. Bd. 79, pp. 129-200.

NIJENHUIS, G. H. W. (1960) — A paleomagnetic study of the Permian volcanics in the Nahe region (SW Germany):
Geol. & Mijnb. 40, 1, pp. 26-28.

OGILVIE GORDON, M. M. (1899) — The Torsion-Structure of the Dolomites with description and map of Sella Massive:
Q. Journ. Geol. Soc. London, Vol. 55, p. 560.

———, (1927) — Das Grödener-, Fassa- und Enneberggebiet in den Südtiroler Dolomiten:
Abh. Geol. B. Anst. Band XXIV, Hft. 1-2.

———, (1929) — Geologie des Gebietes von Pieve (Buchenstein), St. Cassian und Cortina d'Ampezzo: Jahrb. Geol. B. Anst., Wien, Vol. 79, pp. 357-424.

———, 1934) — Geologie von Cortina d'Ampezzo und Cadore:
Jb. Geol. B. Anstalt. Bd. 84, 1-4, pp. 59-214.

OGILVIE GORDON, M. M., and PIA, J. (1940) — Zur Geologie der Langkofelgruppe in den Südtiroler Dolomiten:
Mitt. Alpenländ. Geol. Ver. (Mitt. Geol. Ges. Wien) Band 32, pp. 1-118.

PIA, J. (1923) — Untersuchungen über die Tektonik der Lessinischen Alpen. Denkschrift des naturhistorischen Vereins, Wien.

PIERCE, W. G. (1960) — The „break-away" point of the Heart Mountain detachment fault in northwestern Wyoming:
Geol. Survey Prof. Paper 400-B, 106.

RAMBERG, H. (1963) — Experimental study of gravity tectonics by means of centrifuged models:
Bull. Geol. Instit. Univ. of Uppsala, Vol. 42, pp. 1-97, 53 fig.

RAVEN, Th. (1959) — Dérive continentale causée par courants dans le substratum:
Annales Guébhard, 35/36 (1959-1960), pp. 67-118.

REITHOFER, O. (1928, a) — Geologie der Puezgruppe, (Südtiroler Dolomiten):
Jb. Geol. B. Anstalt, 78, 1-2. pp. 257-326.

———, (1928, b) — Geologie der Sellagruppe, (Südtiroler Dolomiten):
Jb. Geol. B. Anstalt, 78, 3-4, pp. 529-579.

RICHTHOFEN, F. VON (1860) — Die geognostische Beschreibung der Umgegend von Predazzo, Sanct Cassian und der Seiser Alpe in Süd Tirol. Gotha (Perthes).

RITTMANN, A. (1960) — Vulkane und ihre Tätigkeit. F. Enke Verlag, Stuttgart.

ROSSI, D. (1957) — Gli aspetti morfologici delle cime dolomitiche:
Boll. Soc. Geol. Ital. Vol. 76, I. pp. 46-66.

———, (1960) — Sintesi tettonica del gruppo montuoso della Costabella-Valfredda-Ombretta, (Dolomiti occidentali):
Rendiconti Acc. Naz. dei Lincei, ser. 8, Vol. 28, fasc. 3, pp. 382-385.

ROYAL DUTCH/SHELL group of companies (1958) — Standard Legend, Exploration and Production Departments. The Hague.

RUTTEN, M. G., EVERDINGEN, R. O. VAN, and ZIJDERVELD, J. D. A. (1957) — Paleomagnetism in the Permian of the Oslo graben (Norway) and of the Estérel (France):
Geol. & Mijnb. N. S., 19, 6. pp. 193-195.

SACERDOTI, N. and SOMMAVILLA, E. (1962) — Pillowlave, Ialoclastiti e altre formazione vulcanoclastiche nella Regione Dolomitica Occidentale:
Stud. Trentini Sci. Nat. Anno 39, n. 3. pp. 423-473.

SALOMON, W. (1895) — Geol. und Pal. Studiën über die Marmolata:
Paleontografica, Vol. 42.

SANFORD, A. R. (1959) — Analytic and experimental study of simple geologic structures:
Bull. Geol. Soc. Am. Vol. 70. pp. 19-52.

SCHWARZ, E. J. (1962) — Geology and paleomagnetism of the valley of the Rio Aragòn subordan north and east of Oza, Spanish Pyrenees, Prov. of Huesca:
Estudios Geologicos. Ph. D. thesis Utrecht.

SCHIEFERDECKER, A. A. G. (1959) — Geological Nomenclature.
Noorduyn & Zn. N.V., Gorinchem.

SEIBOLD, E. (1955) — Ein Hangrutsch als tektonisches Modell:
Neues Jahrb. Geol. Pal. Mh. 1955, 7, pp. 278-297.

SIGNORINI, R. (1951) — Osservazioni sulla struttura e la morfologia delle Dolomiti orientali:
Boll. Soc. Geol. Ital., 70, 3, pp. 545-564.

———, (1955) — Discutendo sulle interpretazioni tettoniche delle Dolomiti:
Boll. Soc. Geol. Ital., 74, 1, pp. 150-157.

SITTER, L. U. DE (1956) — Structural geology. McGraw-Hill Book Comp. New York.

TRAUTWEIN, S. (1920) — Zur Geologie der Geisslergruppe im Villnös. Diss. Tübingen, 1920.

TREVISAN, L. (1939, a) — Il gruppo di Brenta.:
Mem. Ist. Geol. Univ. Padova, 13.

———, (1939, b) — A proposito di una recente monografia e carta geologica sul Gruppo di Brenta di J. Wiebols: Stud. Trent. Sci. Nat., Vol. 20, Trento.

TRUSHEIM, F. (1960) — Mechanism of salt migration in northern Germany:
Bull. A. A. P. G., T. 44, n. 9, pp. 1519-1540.

VECCHIA, O. (1957) — Significato del fascio tettonico giudicario-atesino:
Boll. Soc. Geol. Ital. Vol. 76, 1, pp. 81-135.

VENZO, S. (1934) — Il Neogene del Trentino, del Veronese e del Bresciano. Trento.

VENZO, G. A. (1962) — Geologia della regione dalla confluenza Val di Cembra-Val d'Adige all'Altipiano di Lavazè, (Trentino-Alto Adige):
Mem. Mus. di Storia Nat. della Ven. Trident. Anno 25-26, Vol. 14, fasc. 1.

WELLER, O. (1920) — Zur Geologie der Langkofelgruppe in Südtirol. Diss. Tübingen 1920.

WENK, E. (1953) — Principelles zur geologisch-tektonischen Gliedering des Penninikums im zentralen Tessin:
Ecl. Geol. Helv., 46, pp. 9-22.

———, (1955) — Eine Strukturkarte der Tessiner Alpen: Schweiz. Min. Petr. Mitt., 35, 2, pp. 311-319.

WIEBOLS, J. (1938) — Geologie der Brentagruppe:
Jb. Geol. B. Anstalt, Wien, 88, Heft 3, 4. pp. 261-350.

WINKLER VON HERMADEN, A. (1957) — Geologisches Kräftespiel und Landformung.
Springer-Verlag, Wien.

## APPENDIX

Late August 1963, when the printing of this thesis was already almost completed, the author had the opportunity of making a joint excursion in the Dolomites with Professor Dr P. Leonardi from the University of Ferrara and Professor Dr R. W. van Bemmelen from the University of Utrecht. Also Dr A. Bosellini, Dr M. Nardin and Prof. Dr E. Semenza (all from Ferrara) joined in this field trip.

The object of this excursion was a confrontation of the diverging views with the facts of nature, and an exchange of ideas on the structural concepts.

We wish to pronounce our sincere thanks to Professor Dr Leonardi for his generous hospitality, his kindness, and his great scientific spirit to allow us this opportunity for a team work discussion in the field. During the trip it appeared that, on the one side, the Italian group had some rather serious misconceptions on the structural ideas of the Utrecht school of geologists, whereas, on the other the clear expounding of the geologic facts on the Dolomites by Professor Leonardi and his co-operators elucidated many aspects for the Dutch part of the group.

It is perhaps advantageous to restate first briefly the broader concept of Van Bemmelen on the structural history of the Dolomites and next some of the more subordinate points, discussed during this excursion.

According to Van Bemmelen stress fields of various magnitude can be distinguished in the structural evolution of the south flank of the austro-alpine range. During the cretaceous "Flysch phase" ("Gosau phase") the great austro-alpine nappes advanced northward, and the sedimentary epiderm of the Dolomites was transported northward more or less passively on the back of its crystalline basement (derma). The latter advanced over the plastic bathyderma. Some broad warping of the basement complex (derma) of the Dolomites may have occurred already during this stage, though no definite examples of such undulations are known. The complications (imbrications, repetitions of thrust nappes) occurred in the frontal parts of the advancing derma farther north, which are now exposed in the central Alps.

The structural evolution of the Dolomites is almost entirely confined to the cenozoic "Molasse phase" of the east-alpine orogenesis. In old tertiary time the uplift of the austro-alpine geanticline started and at the same time the focal area of the alpine orogenesis in the Northern Adriatic began to subside. This collapse of the Adriatic tumor is comparable to the young cenozoic subsidence of the Thyrrenean one, which formed the focal area of orogenesis in the western part of the Mediterranean (cf. * Voute, 1963, sheet 15-17).

The geanticlinal uplift (primary tectogenesis) caused a first order gravitative stress field of great regionality and low intensity, directed towards the south. This resulted in secondary tectogenesis (gravity tectonics) of decreasing order of magnitude in the epiderm and the basement of the southern flank of the austro-alpine geanticline.

First order gravity tectonics occurred in two stages: a) There was a general tendency for southward décollement of the sedimentary permo-mesozoic epiderm, for example SSE-ward in the Val-di-Non area (Van Hilten, 1960). We found asymmetric southward folds in the upper part of the epiderm along the northern border of the NW Dolomites which were probably caused by this initial stage of tertiary gravity tectonics too. b) Great blocks of the basement subsided, which subsidence progressed stepwise from the northern Adriatic towards the north. We can distinguish: (A) the Venetian block between the Venetian and the Bassano basement faults (De Boer, 1963) which subsided probably in middle eocene time; then followed the subsidence of (B) the block of the southern Limestone Alps between the Bassano and Sugana faults in eo-oligocene time, and (C) finally the block of the Dolomites between the Sugana fault in the south and the Judicaria-Pusteria faults in the north (probably in late oligocene time).

The first order gravity tectonics created stress fields of second order with a regionality restricted to the Dolomites block only. Their effects were in the first place a tendency of the derma to slide southward. At the southern side of the Dolomites dermal folds originated (such as the Pale-di-San-Martino syncline and the Bocche anticline with quartz porphyries exposed in its core). At the northern side of the Dolomites block tension features came into existence, such as the antithetic, normal, northward hading faults of Tires and Funes. The sedimentary epiderm reacted with adjustments to these late oligocene deformations of the basement (for example the bending over of the Funes fault, the sliding of the M. Tullo-M. Putia group, the initial formation of the Marmolada bulge, and the SW-ward movement of the epiderm in the NE Dolomites).

Meanwhile, erosion had started in the Dolomites. At first the drainage pattern was guided by the above mentioned deformations. But as soon as the valley floors had reached the ladino-carnian rocks of widely different lithology, a selective erosion proceeded. The ladino-carnian reef masses were carved out as the partly volcanic San Cassiano and La Valle strata were removed more easily. This created local gravitative stress fields of third order magnitude, but of great intensity. In this stage the local mass circuits became active, accompanied by summit thrusting and summit folding, and lateral diapirism towards the valley floors.

Some more subordinate points in which our ideas need some modification after the joint discussions are mentioned below.

We should like to point out that our use of the term diapirism has been used in a broad sense, indicating horizontal and vertical movements of plastic matter on account of load pressure. The resulting structures will be knee folds or domes in a primary stage which may develop gradually in really diapiric structures with abnormal contacts in the ultimate stage of development (diapirism in a strict sense).

For the M. Picio block (chapter VI, 2, b) we suggest a shift of accent. It seems to belong first of all to the diapiric fringe, pushed up around the Puez-Gardenaccia-Odle group, whereas in the second place some sliding of the mass took place. The connection with the anticlinal structure to the SE of it has more or less been preserved.

We suggested in chapter VI, 2, d a diapiric origin for the "line of Gardena". Discussions with the italian members of the field team made this less probable and we are now inclined to explain this northward upthrust as a part of a deformation along a spoon-shaped thrust plane affecting also the basement. It should be comparable then to the analogous structure below the M. Tullo-M. Putia group north of the the Funes fault (which can be compared to the Tires fault). The deformation of the rigid Gardena sandstones along the "line of Gardena" is then also better conceivable.

Professor Leonardi accepts a slight northward sliding and clockwise rotation of the Sasso Lungo group. His concept may be combined without much controversy with our ideas on the structural development of the Sasso Lungo group and the Col Rodella area.

The Latemar group (not discussed in our thesis) does not show squeezing away of its underlying plastic series, as was pointed out by the Italians. According to Van Bemmelen this might result from the presence of the intrusive complex of Predazzo in its centre, acting as a rigid, supporting base. Further observations are needed to test this hypothesis.

For our Campolongo dome structure Professor Leonardi and Professor Semenza suggested compression as a cause of origin. We agree with them, and think that it is the combined effect of confluence of plastic matter from around and a SW-ward push of the SW-ward sliding sedimentary cover of the NE Dolomites (as we discussed in our chapter VI, 3).

Finally the small diapir of Werfen strata in the Badia Valley (fig. 30), which we thought to be lower Werfen, in reality turned out to be composed of upper Werfen strata. Professor Leonardi established this since he collected the following fossils in it: Tirolites cassianus (Quenst.), Gervillia sp., Claraia sp., Homomya fassaensis, var. brevis (Bittner), Naticella sp.

Professor Van Bemmelen observed recently in the Sesto Valley at Ausser Gsell (1954 m), NE of the Cima Tre Scarperi (NE Dolomites) a complicated anticlinal, NE-ward directed structure in Bellerophon and Werfen strata. It resulted probably from the squeezing out of these strata from beneath the dolomites of the Gsellknoten (2864 m) and the Cima Tre Scarperi (3152 m).

* Voute, C. (1963): Essai de synthèse de l'histoire géologique des environs d'Aine Fakroun-Aine Babouche et des regions limitrophes (Algérie orientale). Thesis Utrecht.

## EPILOGUE

And Job again took up his discourse, and said:
"Surely there is a mine for silver, and a place for gold which they refine.
Iron is taken out of the earth,
and copper is smelted from the ore.
Men put an end to darkness,
and search out to the farthest bound
the ore in gloom and deep darkness.

They open shafts in a valley away from where [men live;
they are forgotten by travellers,
they hang afar from men, they swing to and fro.
As for the earth, out of it comes bread;
but underneath it is turned up as by fire.
Its stones are the place of sapphires
and it has dust of gold.

That path no bird of prey knows,
and the falcon'eye has not seen it.
The proud beasts have not trodden it;
the lion has not passed over it.

Man puts his hand on the flinty rock,
and overturns mountains by the roots.
He cuts out channels in the rocks,
and his eye sees every precious thing.
He binds up the streams so that they do not trickle,
and the thing that is hid he brings forth to light.

But where shall wisdom be found?
And where is the place of understanding?
Man does not know the way to it,
and it is not found in the land of the living.
The deep sea says, 'It is not in me',
and the sea says, 'It is not with me'.

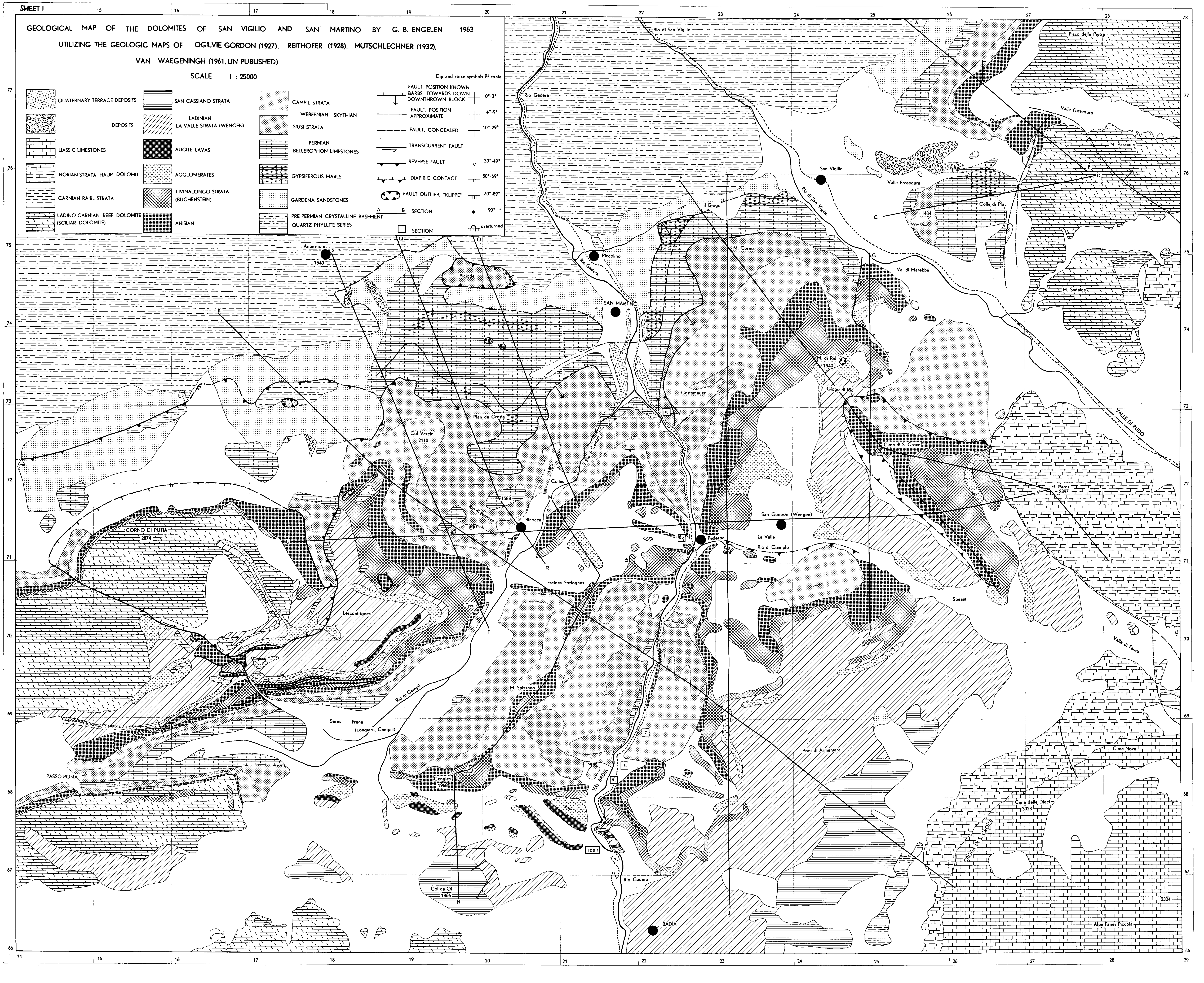
It cannot be gotten for gold,
and silver cannot be weighed as its price.
It cannot be valued in the gold of Ophir,
in precious onyx or sapphire.
Gold and glass cannot equal it,
nor can it be exchanged for jewels of fine gold.
No mention shall be made of coral or of crystal;
the price of wisdom is above pearls.
The topaz of Ethiopia cannot compare with it,
nor can it be valued in pure gold.

Whence then comes wisdom?
And where is the place of understanding?
It is hid from the eyes of all living,
and concealed from the birds of the air.
Abaddon and death say,
'We have heard a rumour of it with our ears'.

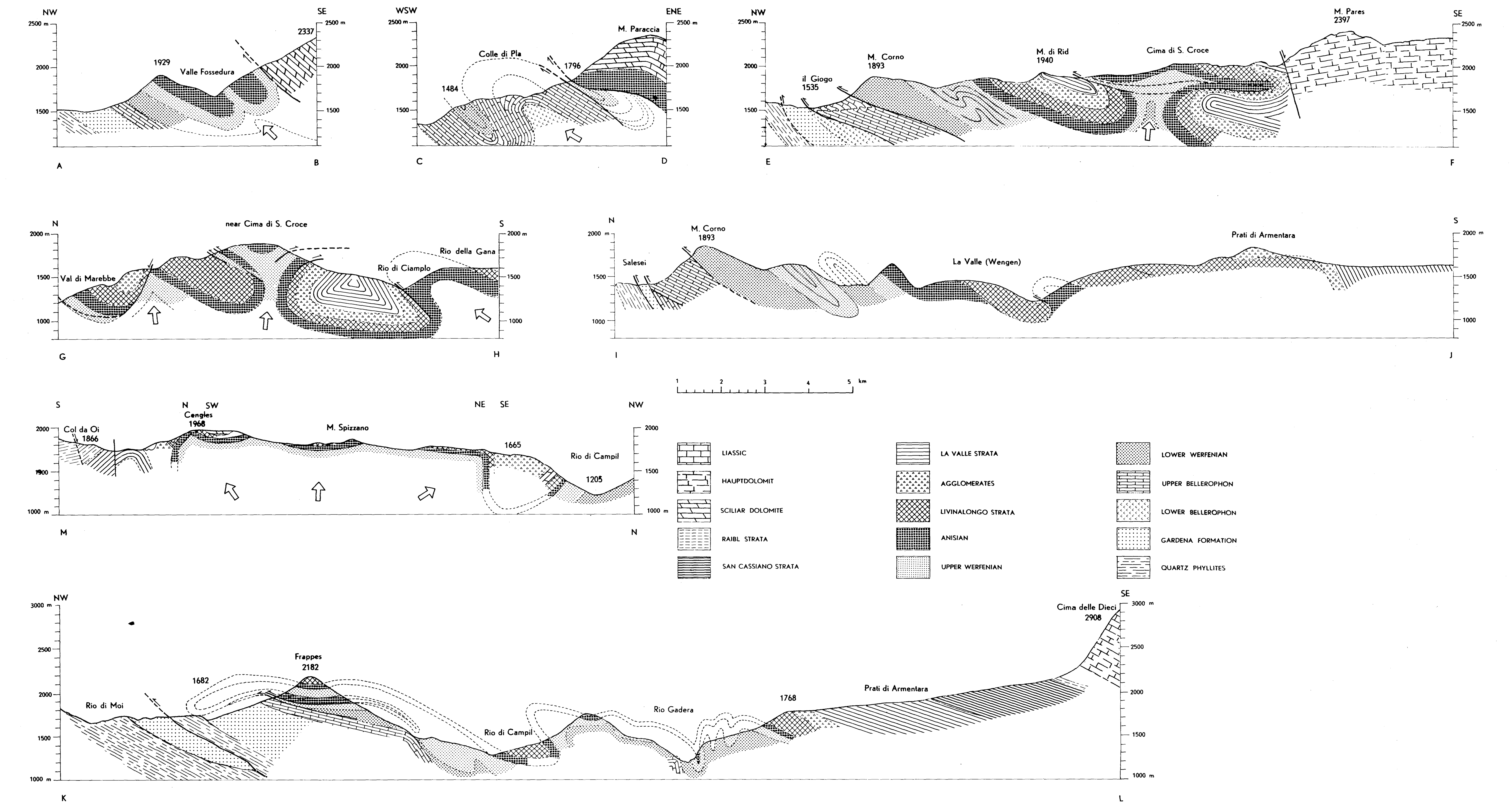
God understands the way to it,
and he knows its place.
For he looks to the ends of the earth,
and sees every thing under the heavens.
When he gave to the wind its weight,
and meted out the waters by measure;
when he made a decree for the rain,

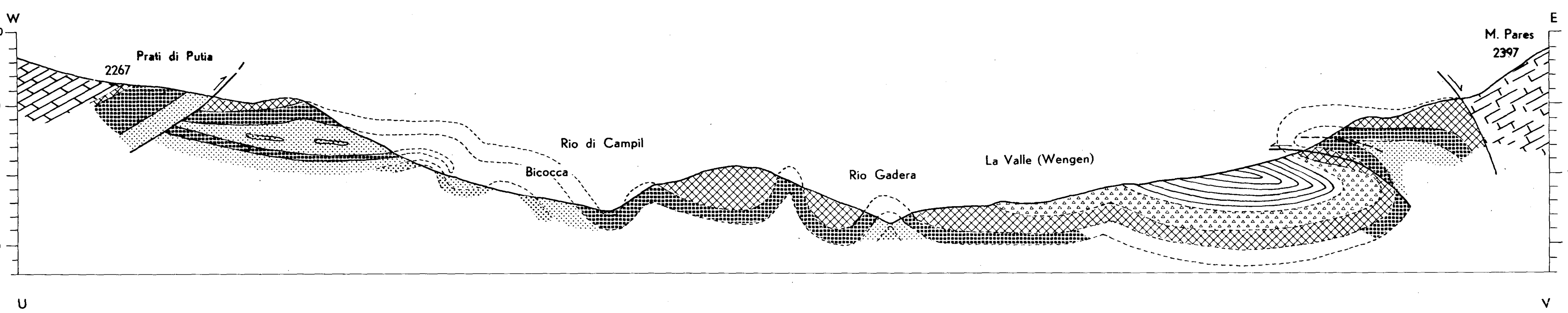
and a way for the lightning of the thunder;
then he saw it and declared it;
he established it, and searched it out.
And he said to man,
'Behold, the fear of the Lord, that is wisdom;
and to depart from evil is understanding' ".

from: The Holy Bible, revised standard version, Job 28.
(Thomas Nelson and Sons Ltd, Edinburgh, 1957).


SHEET I
GEOLOGICAL MAP OF THE DOLOMITES OF SAN VIGILIO AND SAN MARTINO BY G. B. ENGELEN 1963
UTILIZING THE GEOLOGIC MAPS OF OGILVIE GORDON (1927), REITHOFER (1928), MUTSCHLECHNER (1932), VAN WAEGENINGH (1961, UN PUBLISHED).
SCALE 1 : 25000
QUATERNARY TERRACE DEPOSITS
DEPOSITS
LIASSIC LIMESTONES
NORIAN STRATA HAUPT DOLOMIT
CARNIAN RAIBL STRATA
LADINO-CARNIAN REEF DOLOMITE (SCILIAR DOLOMITE)
SAN CASSIANO STRATA
LADINIAN
LA VALLE STRATA (WENGEN)
AUGITE LAVAS
AGGLOMERATES
LIVINALONGO STRATA (BUCHENSTEIN)
ANISIAN
CAMPIL STRATA
WERFENIAN SKYTHIAN
SIUSI STRATA
PERMIAN
BELLEROPHON LIMESTONES
GYPSIFEROUS MARLS
GARDENA SANDSTONES
PRE-PERMIAN CRYSTALLINE BASEMENT QUARTZ PHYLLITE SERIES
FAULT, POSITION KNOWN BARBS TOWARDS DOWN DOWNTHROWN BLOCK
FAULT, POSITION APPROXIMATE
FAULT, CONCEALED
TRANSCURRENT FAULT
REVERSE FAULT
DIAPIRIC CONTACT
FAULT OUTLIER, "KLIPPE"
SECTION
SECTION
Dip and strike symbols of strata
0°-3°
4°-9°
10°-29°
30°-49°
50°-69°
70°-89°
90°
overturned
Rio di San Vigilio
Pizzo delle Pietre
Rio Gadera
Valle Fossedura
M. Paraccia
San Vigilio
Valle Fossedura
Colle di Pla
1484
il Giogo
Rio di San Vigilio
Antermoia
1540
Piccolino
Rio Gadera
M. Corno
Val di Marebbè
Piciodel
M. Sadalce
SAN MARTINO
M. di Rid
1940
Costamauer
Giogo di Rid
Plan de Crosta
VALLE DI RUDO
Col Vercin
2110
Rio di Campil
Cima di S. Croce
2020
Colles
1588
Rio di Bicocca
M. Pares
2397
San Genesio (Wengen)
Bicocca
Pederoa
La Valle
Rio di Ciamplo
CORNO DI PUTIA
2874
Freines Forlognes
Lescontrignes
Ties
Spessa
Valle di Fanes
M. Spizzano
Rio di Campil
Seres
Frena
(Longiarù, Campill)
Prati di Armentara
Cima Nove
PASSO POMA
Cengles
1968
VAL BADIA
Cima delle Dieci
3023
CRODA DI S. CROCE
Col da Oi
1866
Rio Gadera
2324
BADIA
Alpe Fanes Piccola

SHEET II




SECTIONS BELONGING TO THE GEOLOGICAL MAP OF THE

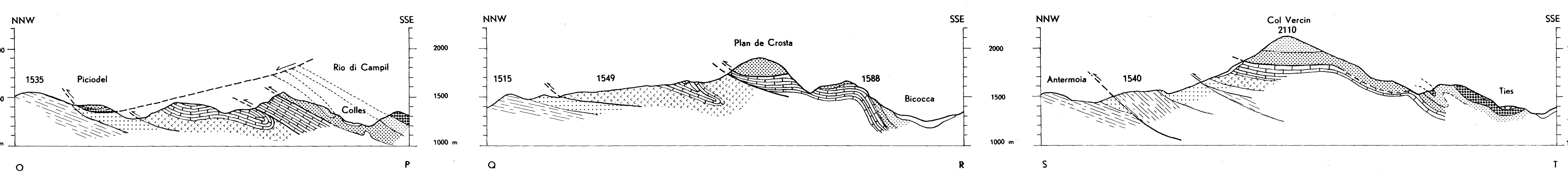
DOLOMITES OF SAN VIGILIO AND SAN MARTINO

NW DOLOMITES, N ITALY

SCALE 1 : 25000

G. B. ENGELEN

1963



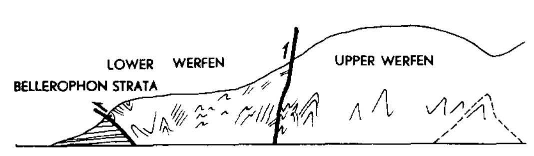
SHEET III

DETAIL SECTIONS OF OUTCROPS OF PLASTIC TRIASSIC STRATA ALONG THE ROAD BADIA - SAN MARTINO (BADIA VALLEY), in the DOLOMITES OF SAN VIGILIO AND SAN MARTINO. NW DOLOMITES, N ITALY

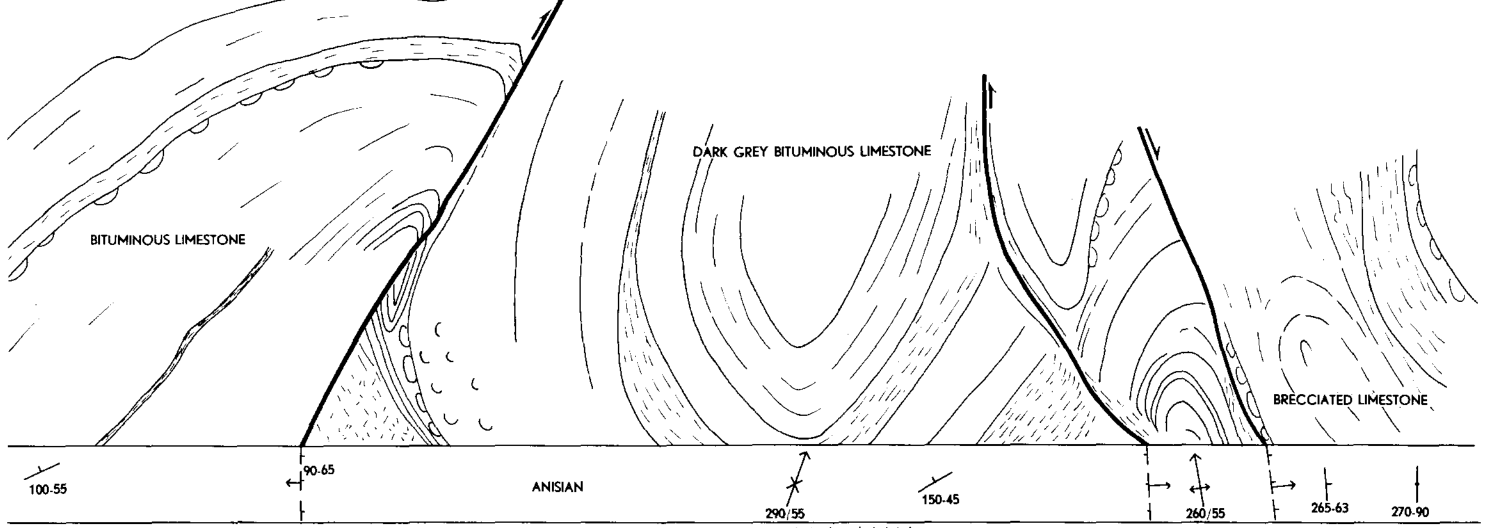
G. B ENGELEN 1963

SHEET III

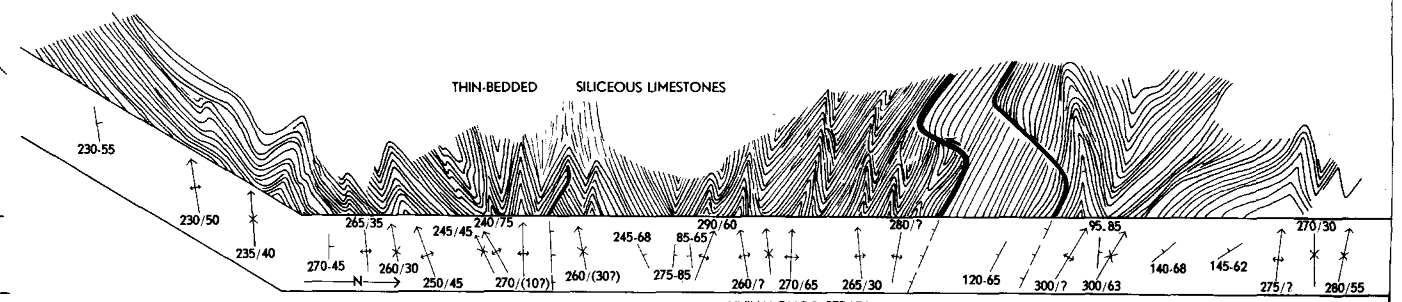
SCALE 1 : 300



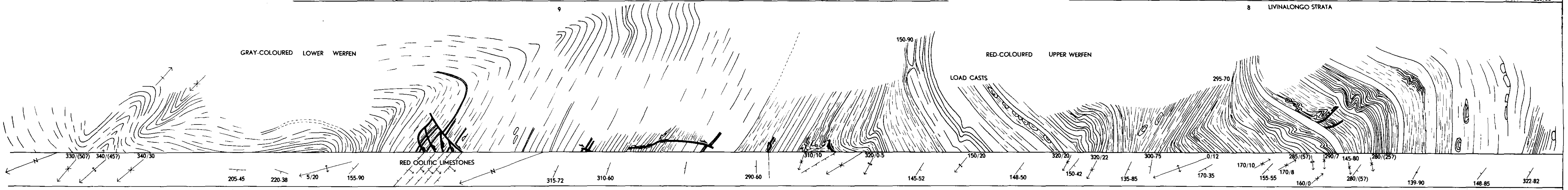
10



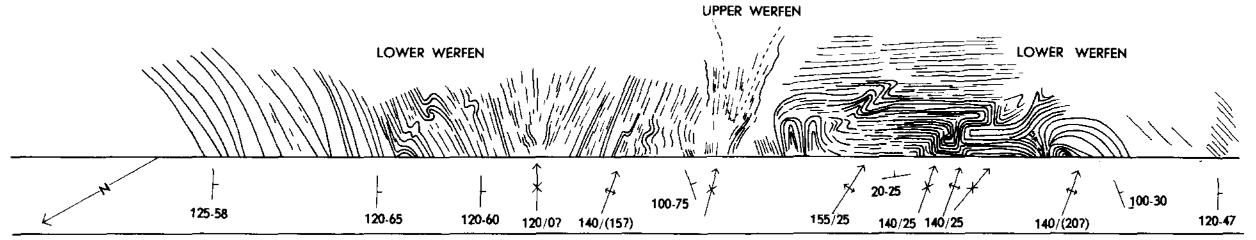
9



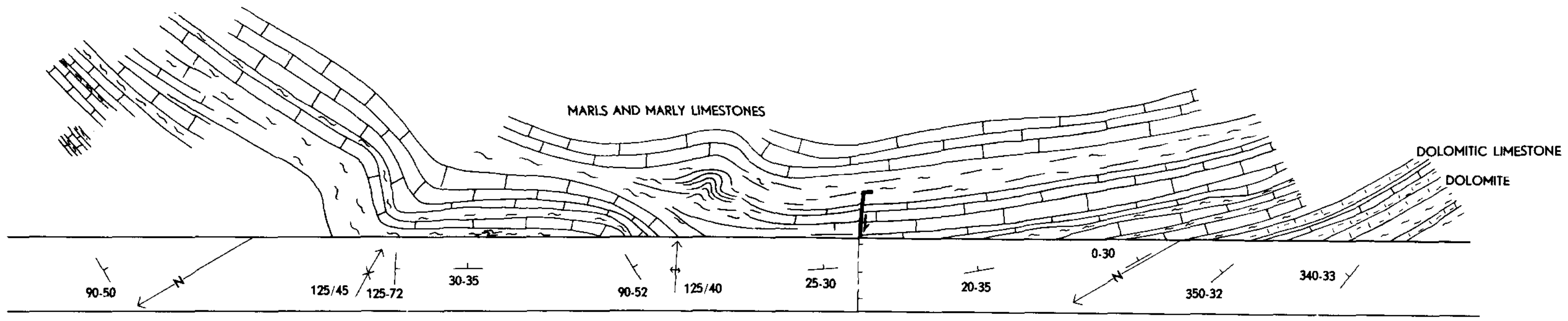
8 LIVINALONGO STRATA



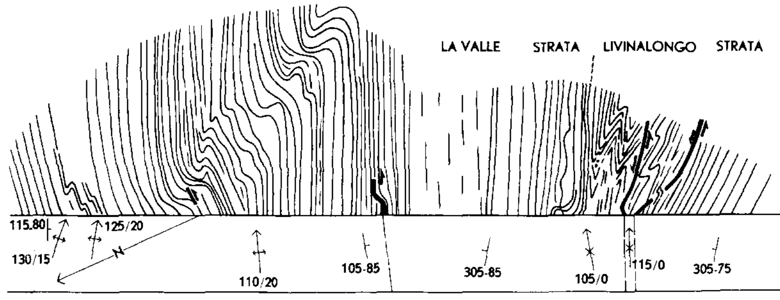
7



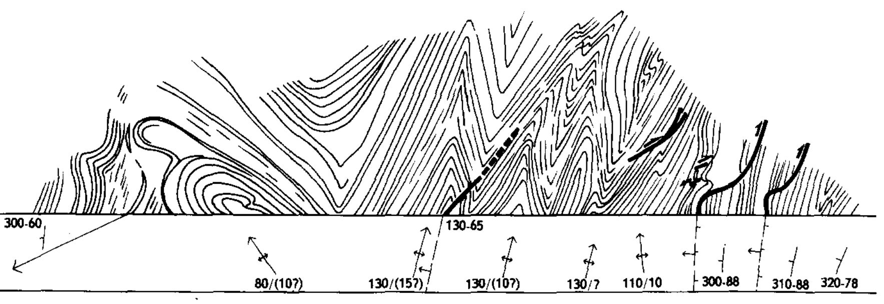
6



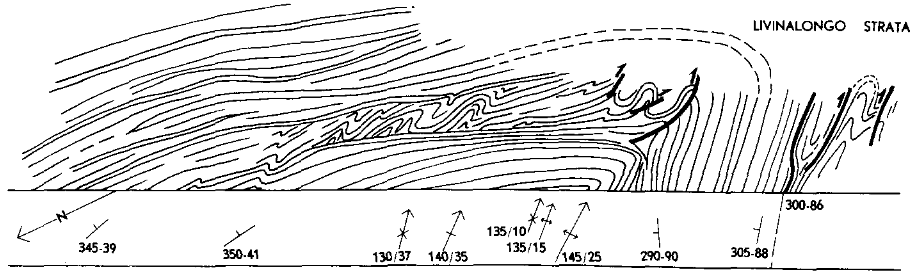
5 ANISIAN



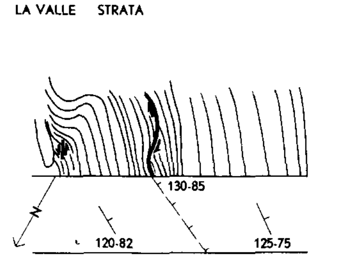
4



3



2



1